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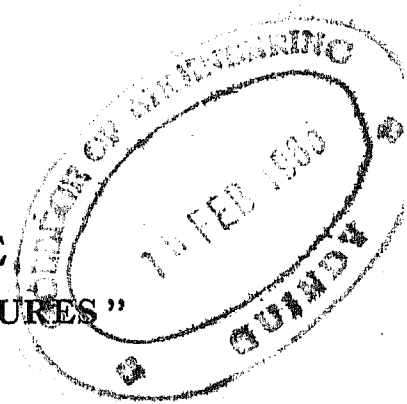
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THE THIRTY-FIRST KELVIN LECTURE

"THERMODYNAMICS AND THE LOWEST TEMPERATURES"

By C. G. DARWIN, M.C., Sc.D., F.R.S.

(Lecture delivered before THE INSTITUTION, 25th April, 1940.)



In delivering before this Institution a lecture which is to be associated with the memory of Kelvin, it would be most natural to select some aspect of his work which was electrical in character or, at all events, which stood in the main line of the great developments in dynamics for which he was responsible. As will be seen from my title, however, I am not going to do this, but instead I am going to take up an aspect of the other and, as I think, the greater work which he accomplished when he established the principles of thermodynamics.

Thermodynamics is a tremendously general subject, and one of its generalizations appears to be that people fall into two sharply-divided classes, those who definitely like it and those who definitely do not, the last being in a considerable majority. The reason is very plain, but it is not flattering to the human intellect. When one studies a textbook on the subject, one gets a beautiful chain of logical argument which conducts the reader step by step steadily and inevitably to the end. The argument forces one, fairly willingly, to believe in the existence of absolute temperature, and then a good deal less willingly in that of entropy, and then goes on to things like free energy and thermodynamic potentials which seem almost too abstract to be believed in at all. I think that a good deal of most people's difficulty comes simply from lack of practice in problems in the subject. In ordinary dynamics and in electricity everyone goes through a drill of working out little problems. These are often of an absurdly artificial kind, but they do possess the virtue of giving one the right habits of thought. But for such practice many of us would find the same sort of difficulty in thinking about, say, self-induction as we do about entropy. By handling choking-coils and doing examples on circuits we can *feel* what self-induction is, but, unfortunately, nobody has succeeded in inventing similar problems to make us feel what entropy is. The result, anyhow, is that many have the same emotions of doubt and suspicion about thermodynamics as we do when an economist tries to convince us by argument of some opinion which is contrary to our own politics. I count it as the greatest exhibition of Kelvin's genius that, as a young man of 24, he could find his way with confidence through this difficult chain of reasoning and could get his argument right so that, although he must have had the difficulties I have described to an enhanced degree, he yet emerged at the other end with a full-grown doctrine which has stood the test of time and which (apart from one important supplementary principle added much later) remains unaltered since the date, 92 years ago, when he first enunciated the idea of absolute temperature.

My aim to-day is to describe a particular branch of physics, the attainment of great cold, which in itself constitutes an epitome of the subject of thermodynamics. In order to make the subject clear, I propose first to develop what seems to me the easiest way of acquiring a *feeling* for thermodynamics, so that one can foresee what is going to happen and not be compelled to trust to purely formal, though perfectly correct, mathematical reasoning. This is made possible by the use of statistical mechanics, a subject which was started in the middle of last century, but which has only reached its full stature since the beginning of the present century. Its main developments originate from Maxwell, Boltzmann and Gibbs, and it is regrettable to record that Kelvin himself found it an entirely uncongenial way of looking at things.

THE EQUIPARTITION OF ENERGY

The subject of thermodynamics goes, of course, beyond the familiar principles of ordinary dynamics, and it is therefore natural that we must have an extra principle in order to be able to work it. This principle which I am going to use is the *equipartition of energy*, and perhaps I had better remind you of how it works. Suppose that we have a closed vessel containing a gas, say oxygen. The molecules are all moving rapidly to and fro in all directions with various speeds ranging between zero and roughly $\frac{1}{4}$ mile a second. At intervals they collide with one another, but a molecule is such a small thing that at ordinary pressures it spends far the greater part of its time describing a straight line independently. When two happen to meet, the collision changes their directions and speeds, but the sum of their energies is unchanged. The molecules also collide with the walls of the vessel and bounce off, and it is this continual bombardment that constitutes the pressure of the gas; we shall have more to say about it later. If we imagine that we knew the motion of all the molecules at some instant of time we could work out their kinetic energies, and adding them together we should have the total energy of the gas in the vessel; a perfect gas has no potential energy, and oxygen is nearly perfect. We could divide this total by the total number of molecules, and so get the average energy of a molecule. Moreover, since the collisions do not change the energy, the average will be constant as time goes on. It should be noted that when we talk about an average we often go far beyond the strict idea by thinking of the individuals as all coming rather close to its value; for example, when we say the average height of a man is 68 in. we tend to expect that most men will be somewhere between, say, 58 in. and 78 in. But this is going far beyond the idea of an average, as may be seen by con-

sidering that a man with a batting average of 68 will often score centuries, and sometimes nothing, and it is in this last accurate sense that I am using the idea here. I am not implying that an individual molecule need have energy anywhere near the average at a given instant.

The fact that we can speak of the average energy of the oxygen molecules in this way is obvious and tells us nothing. But suppose that we take two gases together, mixing, say, hydrogen with the oxygen. The atoms of the two kinds can now collide with one another and interchange energy, and the question arises of what happens. Nobody could work out the result in detail, but the theorem of the equipartition of energy tells us the answer. It asserts that the average energy of a hydrogen molecule will be equal to that of an oxygen, no matter what the proportions of the two gases that may be mixed together. Since energy is proportional to the square of speed, and the oxygen molecule is 16 times as heavy as the hydrogen, it follows that the hydrogen molecules are on the average moving 4 times as fast as the oxygen.

This is the simplest example of the theorem—simplest because we have taken perfect gases. But it is true in other cases, so that any part of any system that is capable of exchanging energy will take a share of the energy and, on the average, will have exactly the same amount of kinetic energy as the molecule of the gas. For example, the atoms of the wall of the containing vessel are affected by the collisions of the gas molecules, since it is through them that we are able to measure the pressure. On the average each molecule of the wall will acquire as much *kinetic* energy as a molecule of the gas, but, unlike a molecule of the gas, it possesses also potential energy and this will also demand a share in the equipartition, so that on the average the energy is double as much.

Now, when a number of things are intimately mixed together they are thereby compelled to come to the same temperature. We identify the average energy of equipartition with the temperature, and it may be shown that in fact it is identical with the temperature measured on Kelvin's absolute scale. The average energy of an atom of a monatomic gas is $\frac{3}{2}kT$, where k is a known very small constant. Here is a link with pure thermodynamics, but it is still an incomplete one since thermodynamics makes great play with a second quantity, namely entropy. For a full consideration of statistical mechanics it is of course indispensable to fit entropy into the scheme, but fortunately for my present purposes I can do without it, since it will suffice me to take the principle that systems in contact arrive at an equipartition of their energy, and so I shall not need to make any further mention of entropy.

The principle of equipartition has never been proved. It was first enunciated in 1845 by Waterston, the keeper of a stationery shop in Edinburgh, but his paper was rejected by the Royal Society as being of insufficient interest; years afterwards it was published as an act of historical piety. Later it was enunciated again by Maxwell, but was not proved. Many have tried to find the proof, but nobody has succeeded. This may seem rather disappointing at first sight, but I think the modern view of most physicists would be that the grapes really are sour; in fact, it is unprovable, but we do not want to prove it.

This is not because it is untrue, but because it is only true on the average and there are always exceptional cases where it would not hold. But, subject to certain assumptions, it can be shown to be true in such a vast preponderance of cases that it will be legitimate to forget the exceptions.

I have enunciated the theorem in its simplest case and have over-simplified it in so doing. In the first place, I have said nothing about the rotations of the molecules, which will also share in the equipartition. Thus a monatomic gas takes three shares per molecule, each of $\frac{1}{2}kT$, one for each dimension of space, whereas a diatomic takes five, since it can turn about two directions in space. More complicated molecules may have six shares, but for most of them other effects enter which I shall not discuss. Each atom of a solid usually has six units, three for the components of kinetic energy and three for potential energy. But there is a much more important modification which must be described.

The rule of equipartition implies the celebrated law of Dulong and Petit, that the specific heats of equal numbers of atoms of different substances should be the same. This law holds for most substances, but long ago certain puzzling exceptions were known; for example, the diamond has a much smaller specific heat than it should have. Moreover, the law implies that just as much energy should be taken to raise a body from 1° K. to 2° K., as to raise it from the freezing point 273° K. to 274° K.; whereas it was found at the end of last century that at these low temperatures the specific heats of all substances become very small—the diamond only differs from the rest in that its specific heat has started dropping earlier. This mysterious fact was later fully explained by means of the quantum theory, and arises from the rule that energy cannot be taken up by the atoms in arbitrary amounts but only in definite units. The way the process works may be described by a metaphor which is perhaps no more of a straining of common sense than are most other metaphors. Imagine that we have a large town, the health of which is cared for by a number of doctors. There are rich men's doctors and poor men's doctors. The rich ones charge large fees and get rather few patients, while the poor ones work hard and get many small fees. I shall suppose that it is a rule of the Medical Council that no doctor is allowed to change the scale of his fees. Then, when the town is prosperous, on the whole the doctors will all earn about the same, because when a medical student qualifies he will select whichever branch of the profession appears most profitable, so that the law of supply and demand will hold the two sections of the profession level, and all the doctors will be equally rich. This is the state of equipartition. But now suppose that the town is hit by an economic depression. Everyone suffers, the doctors included, but not equally, for no one will have the money for a large fee, and so whereas all the doctors will be poorer than before, the Harley Street doctors, who are not allowed to lower their fees, will be put right out of business. Consequently the total income of the medical profession will be diminished out of proportion to that of the rest of the community.

This is a metaphorical description of what happens at low temperatures. The matter is made a little harder:

to appreciate because it is not the separate atoms that constitute the units on which the energy is placed; it is combinations of them in the form of elastic waves of vibration. The shorter waves that require large doses of energy are frozen out and get none, and the only ones that get energy are the longer ones which can accept it in small quantities. It is this effect that causes the specific heat to be much less at low temperatures. A purist might object that we certainly no longer have *equipartition*, and therefore ought to call it something different. To my mind that does not matter, and I shall go on calling it so, because the equal partition was the first case that was understood and mastered and the extension to the case of unequal partition follows the same fundamental rule, which in its simplest example leads to equipartition. The term may be taken as a general name, and it would be as unreasonable to object to it as to the word "atom," which means the thing which cannot be split, when it notoriously has been split.

REFRIGERATION BY VAPOURS

We are now in a position to understand the general process of cooling. In all cases it follows the same principle. By some means or other a machine is arranged so that certain components of the system lose energy by doing work on something outside the system. These components thus find themselves with less energy than that with which they started, so that the balance of equipartition is put wrong between them and the other components, those which were not directly affected by the machine. The affected ones therefore proceed to borrow energy from these others so as to try to restore the equipartition. There will not be enough to go round on the old scale, and so the new equipartition will be at a lower value; in other words, the body is cooled. We shall have to consider quite a number of different processes of refrigeration with their two processes of extraction of energy followed by the restoration of equipartition at a lower level.

The oldest way of all of producing cold was the use of ice and salt, but I shall not go into it here. After it came the process of boiling liquids, and this was the only practical one till about 60 years ago. Consider a liquid and the vapour above it. The molecules of the liquid are moving all the time; they are very close together and exert very strong forces on one another, but these forces roughly balance out, since each molecule is being pulled equally in all directions by its neighbours. The molecules in the vapour are capable of the same forces, but are most of the time so far apart that these forces are without much effect. By equipartition the *kinetic* energy of the molecules in the vapour is the same as that of those in the liquid. Consider what happens when a molecule of the liquid comes up to the free surface. It tries to get out, but as it emerges it finds all the other liquid molecules on one side of it, instead of all round, and they tend to pull it back. Only if it has great kinetic energy can it escape, and in doing so it will be slowed down. On the other hand, when a molecule of vapour comes down to the liquid surface it immediately feels the pull of the liquid and is drawn in, and gains speed and energy as it falls in. Thus a molecule emerging from the liquid will carry away with it an unduly large share of kinetic

energy, but will contribute to the vapour an unduly small share, and the converse is true for a molecule entering the liquid. The two processes ordinarily balance one another, because as many are falling from the vapour as are getting out from the liquid. But suppose that we attach an air pump so that the vapour is continually removed. Then the balance is upset and the liquid will be continually losing more and more molecules so as to try to restore the pressure above. All these molecules will be the energetic ones, and their desertion will upset the equipartition of the liquid. The collisions in the liquid will try to restore it, but can only do so at a lower level of energy, and so the temperature will drop.

This was the process employed by most of the earlier workers in the production of cold, at first using liquids such as CO_2 or NH_3 ; and the end of the earliest stage led to a temperature of 160°K . in the hands of Faraday in 1835. It culminated in the liquefaction of oxygen by Olszewski in 1883, by the use of a cascade in which CO_2 abstracted the heat from C_2H_4 , which in turn took it from O_2 . A necessary condition for this method is that each stage at its low pressure should be cold enough to liquefy the next one at its highest pressure. Cascades can be formed for all gases except hydrogen—and helium, which at that time was still undiscovered—but at the lowest nitrogen temperature, of about 60°K ., hydrogen will not liquefy, so that the last stage of liquefaction of gases called for a new method.

I do not propose to discuss how it was first done. It was by a method which is still often used and is very convenient, but it depends on certain of the more recondite properties of gases connected with the fact that they are not quite perfect. Instead I shall take only the simpler method which is now used in most of the industrial plants which make liquid air. It has the advantage that it works for a perfect gas. When a molecule bounces on the wall of the vessel, it comes off at the same speed as it went on. For a smooth rigid wall this is obviously true, and it is also true on the average for a wall composed of molecules at the same temperature as the gas, though we need not consider that at present. Now suppose that part of the wall is movable like the piston in a cylinder. If it is slowly moving back, the molecules which hit it come off at the same relative velocity, and therefore at a reduced absolute velocity. This corresponds, of course, to work done on the piston, and the energy for this work is taken from one of the components of velocity of the molecules. The equipartition of the molecules is thus disturbed and this component proceeds to borrow energy from the other velocity components and from the rotational energy of the molecules, with the result that equipartition is restored but at a lower temperature. A refrigerator working on this principle is simply a reversed Carnot cycle, giving up heat to circulating water on compression at the high temperature and then extracting it at the low pressure and temperature from what in an ordinary engine would be called the condenser. It is a little remarkable that this obvious design took so long in coming, but the main trouble was that it necessarily involves moving parts and that the problem of lubrication was difficult.

With the help of various types of machine based on

these principles, hydrogen and helium can be liquefied and solidified, and temperatures down to a little below 1°K . can be reached, but at about 0.8°K . the process fails. There is no exact point of failure, and the reason of failure might be called purely practical, but that a similar thing occurs in all the other stages of refrigeration. The cause is this: At a temperature of 1°K ., hydrogen is solid and helium liquid, and in both the vapour pressure is very small. Now it is just this vapour that is operative in extracting the energy, and, since there is so little of it to work on, the only way of going further would be to take a much larger piston and cylinder, and this greater size would put up the heat capacity of the machine and increase the difficulty of its heat insulation. Actually, the lowest temperature of about 0.8°K . has been attained by getting liquid helium and then making it evaporate as fast as possible under a powerful pump.

I wish there were time to give an account of some of the surprising things that were discovered in this range of temperatures, but to do so would easily take several hours. So I will only remind you of the existence of superconductivity in certain metals and compounds, with the associated extraordinary magnetic properties, and of that queerest of all substances, liquid helium, which can go to the lowest temperatures without solidifying except under high pressure, while at the lower pressures it refuses to stay in a cup but creeps over the edge out on to the floor. Less exciting but more to our present purpose is the change in the value of the specific heat, which for all substances has become very small at 1°K . The consequence is that when the engine extracts a certain amount of energy from a substance the temperature drops very much more than it would have done if the specific heat had retained its value from ordinary temperatures. Indeed, but for this drop of specific heat it would hardly have been possible to get these low temperatures at all. And then there are the greatly enhanced magnetic properties of many substances at these temperatures, but as it is these that have made possible the next stage in refrigeration we must turn aside to consider briefly the theory of magnetism.

PARAMAGNETIC REFRIGERATION

As is well known, materials may display any one of three different magnetic characters. The majority are diamagnetic. These are weakly repelled from a magnet and their nature will be easily appreciated by the electrical engineer, since it arises from an undamped eddy current induced in each atom as the field is put on and annihilated again when it is cut off. Diamagnetism is a phenomenon of each separate atom or molecule, and is independent of the temperature and therefore of no interest to us here. Then there is ferromagnetism, the ordinary magnetism of iron and nickel. This is an enormously strong effect by comparison, and its theory is moderately well understood: it has interesting thermodynamical features, but they are exhibited mostly at high temperatures and so do not concern us. The third effect is paramagnetism. In this the body is attracted by a magnet, as in ferromagnetism, but about a million times less, so that the weak attractive force is of about the strength of the repulsive diamagnetic force or perhaps rather more. The enormous quantitative difference

between paramagnetism and ferromagnetism is due to a qualitative difference; for in paramagnetism it is the separate atoms that are responsible, whereas for ferromagnetism it is certain very intense interactions between the electrons in the atoms. Paramagnetic susceptibility is very much affected by temperature, and it is this that makes it of interest to us; we must examine its theory.

Think of each atom as containing a little freely-suspended bar magnet. These magnets possess energy and can rotate, and there are interactions between the rotations and the other heat movements of the atoms of the specimen. Therefore there is equipartition between them, and at ordinary temperatures we have to think of the little magnets mostly whirling round rather fast. On account of this whirling they point on the average equally in all directions and the specimen is unmagnetic. But now put it in a magnetic field. We are not concerned with the diamagnetic effect, though it will be present, but there is a second more important effect to consider. Each magnet will now no longer rotate uniformly, but will move like a flywheel a little out of balance. Some go fast, some can barely get over the dead centre, and some may happen to have so little energy that they oscillate instead of rotating. The outcome of this is that when an average is taken the magnets tend to point slightly down the field, and thus the specimen acquires a slight magnetic moment, which agrees in direction with that of the field, and is usually strong enough to swamp the diamagnetic moment in the opposite direction. The paramagnetic moment, depending as it does on the energy of equipartition, will vary with temperature and is found to be inversely proportional to it, so that at low temperatures paramagnetics have greatly increased susceptibilities. If we could get down to the absolute zero, all the magnets would be at rest pointing down the field, and the specimen would be saturated so that no increase of external field could increase its magnetization further. Effects of saturation are observed for some substances at the deepest temperatures, but I do not need to consider them here. It is sufficient to note that the magnetization in a given field will go up as the temperature goes down, since this suggests a method by which conversely we can alter the temperature.

The process was first proposed by Debye and independently by Giauque, and before explaining why it works we will see how the experiment is done. The first work was done with gadolinium sulphate, for the reason that its paramagnetic behaviour is exceptionally well understood, but of late commoner substances such as iron alum have been more used. A specimen, usually in the form of a powder, is first cooled down with liquid helium. It is next placed in a strong magnetic field, as a consequence of which it begins to heat up again, but this heat is also absorbed by the liquid helium. The helium is next removed, so as to insulate the specimen, and then the magnetic field is cut off, and as a consequence the temperature drops immediately to a very low value. Technically the process is of course very difficult, but this drop in a single step to the lowest temperature is in some ways very much simpler than the elaborate sequence of pumping and repumping of vapours that has to be done in the earlier stages of the refrigeration.

We must now try to understand why the process works. As it is a magnetic process it will depend on somehow getting energy out of the little magnets, and we have to see how this is done. A magnet placed in a magnetic field oscillates with a certain frequency, and if the field is weakened the frequency diminishes so that it oscillates more slowly. That is easy, but it is by no means so easy to see what happens to the *amplitude* of the oscillation as the field changes. It is easier to see this by taking the analogy of a pendulum so arranged that its frequency can be gradually altered. To do this we tie a bob W to a long string and make the other end fast at A. The string passes through a hole B in a light frame, and the frame can be slid up and down a groove vertically below A. It is thus only the part BW that swings. If B is low the pendulum is short and swings with a high frequency, but if B is up near A the swing is slow. What happens when we give the bob a measured amplitude of swing with B at the top and then slowly lower B? This is a dynamical problem which at first sight might appear elementary, but it is not quite so simple as it looks, and most students will have gone through their university course, as I did, without having been made to consider it. Still it is not really very difficult, and we can see what happens in a general way without obtaining the detailed solution. The reaction on the frame at B is half the time to the right and half to the left, but whether the bob is to the right or the left the reaction is always slightly upwards, only ceasing to be so at the instants when the bob is vertically below A. If then B is slowly lowered, it is lowered against a force, and so does work, and the bob therefore acquires energy. Conversely, if it is raised the frame absorbs work and the bob loses energy. The solution in detail shows that at every stage the energy of the pendulum is proportional to the frequency. The result is general; when a vibrating system has its frequency of vibration raised it acquires energy from outside, when slowed down it loses energy.

Applying this to our magnets, think of one of them which is doing a small oscillation in a weak magnetic field. If the field is increased the frequency of oscillation will increase, and therefore the energy of the magnet will also increase, the work for it being done by the external field. Conversely, if we start in a strong field and slowly weaken it, the magnet's energy will decrease. Thus when our paramagnetic is put into the strong field the little magnets get more energy than is justified by equipartition and this they share out, so that the specimen heats up. This heat is absorbed by the liquid helium, and the magnets are left with the equipartition energy of the liquid helium. When the field is weakened, the magnets lose most of their energy and so will have very much less than the equipartition amount. They try to restore equipartition by borrowing energy from the other parts of the system, and so the temperature is lowered.

The process works at any temperature for a paramagnetic, but is very feeble at room temperatures. It becomes effective at low temperatures, for two reasons. Firstly, the magnetic susceptibility becomes much bigger, so that attainable magnetic fields become much more efficient; and secondly, the specific heat becomes much smaller, so that a given extraction of energy changes the temperature much more. In this way it comes about that

it only takes a single stage to lower temperature from about 2°K. to about 0.003°K.

Before passing on to the properties at these new temperatures I ought to confess that in one respect I have rather simplified the statement. An atom is not so much like a bar magnet as like an electromagnet. We may liken it to a perfectly conducting ring carrying current. As the field changes, the plane of the ring changes too, and the same things happen to the energy as I have described, but they are rather more complicated because one has to consider a motion something like that of a top and this is more troublesome to think about than that of a pendulum. I might also add that, though the way I have used of watching the energy gives an easier insight into the process, in most cases it is quite troublesome to work out and the orthodox thermodynamic use of entropy is far simpler.

There have been several schools of workers in this field. Giauque in America was the first to apply it, and he has made a detailed study of the properties of matter round about 0.1°K. In such work as this mere record-breaking is not the main thing, and Giauque's work has been as useful as anyone's, even though others have gone much further. De Haas of Leyden has got down to about 0.003°K. , and Simon of Oxford to about the same. In addition to getting to such temperatures, we want to know what they are on the absolute scale, and this calls for more elaborate work. Anybody who has studied the thermodynamics of ordinary temperatures will remember what a troublesome business it was to fix the scale by such methods as that of the Thomson-Joule experiment. As a matter of fact, the new problem has turned out to be rather easier, because heat losses at these low temperatures can be made very small, so that the system can be approximated much more easily to the ideal thermodynamic engine of Carnot and hence the temperature can be measured directly. Even so, it is not easy work, and the lowest temperatures attained are still rather conjectural. Pre-eminent on this side of the problem has been the work of Simon and his collaborators, who have fixed the absolute temperature scale with considerable accuracy down to 0.01°K.

The properties of matter at these temperatures are interesting. Firstly, there is to all intents no vapour left at all; it is this that makes the heat insulation so good. Then the specific heat becomes very nearly simply that of the magnets, since the other parts have so little that they hardly count. But there are technically much more interesting features, and I propose for a few minutes to go rather deeper into theory in order to describe them.

In my description of paramagnetism I spoke of each little magnet as simply exposed to a controllable external magnetic field, but in fact it is of course also in the field of all the other little magnets. As the temperature drops, they all begin to line up and cumulatively to exert forces on one another. Each little magnet cannot be expected to know where the force on it comes from, but will react to the total field acting on it. The result is important and was until very recently most puzzling. The old theory of these local fields was that of Lorentz, and for long it had been accepted without question. According to this theory the susceptibility should be inversely proportional not exactly to T but to $(T - \theta)$, where θ is a calculable

temperature which for most substances should be in the region of 1°K . Below this temperature the substance ought to be capable of becoming a permanent magnet; in the old days the question had only an academic interest, but with the opening-up of this new range of temperatures it was interesting to see whether it would. The experiments failed to find any permanent magnetism at the predicted temperature θ , but there is a faint and rather doubtful suggestion of it at a good deal lower temperature.

This subject is much more exciting than might appear at first sight, because a similar theory was applied for electricity as well as for magnetism, and there it led to such fantastic results that for long nobody was willing to face the problem at all. Just as magnetic permeability is largely due to little magnets tending to point along the magnetic field, so the dielectric constant of a non-conductor is largely due to electric dipoles twisting round under the external electric force. In particular, the large dielectric constant of water is mostly due to the strong electric moment of the two H's that lie in directions roughly at right angles from the O. Now dielectric polarizabilities are mostly much larger than magnetic susceptibilities—something like 10 000 times as large—the consequence of which is that the critical temperature for them is very much higher. For water, this temperature ought to be nearly $1\,000^\circ \text{C}$. This is a fantastic result, for it means that if we fill a hose with water and then bring the ends together, the water ought to become violently polarized with one end positively charged and the other negatively; it should be a strong horse-shoe magnet, only electric and not magnetic. Until about 4 years ago, nobody knew at all why it did not do this, and the theoretical result was so contrary to the facts that anyone who realized the difficulty was frankly terrified of the whole problem. Happily we now know that Lorentz's theory is too simple, and an explanation has been found, by various workers, which removes the trouble by showing that the co-operation between adjacent magnets, or dipoles, needs more thorough discussion than it receives in Lorentz's theory. Nobody even now knows the full answer, but it is quite clear that there is no reason to expect the onset of permanent electrification at the critical temperature, and it is to be conjectured that it will not come at any point above the absolute zero. Reverting to the magnetic case, this same theory applies and removes the expected trouble, but even now the whole subject is not very clear. There are technical points which would be of great interest to electricians, but it would take me too long to go into them properly.

If it is so comparatively easy to get down to 0.003°K , what stops us there? The answer is that for each substance there is a sort of barrier preventing further chilling. One can see that when all the magnets are pointing the same way it will not be possible to get any further chilling anyhow, but thermodynamics shows that some time before this point there must inevitably be a large increase in the specific heat, extending over a certain range of temperature. This rise of specific heat checks the temperature drop, and would make it very hard to get below it. The effect is really a convenience rather than the reverse because, once the specimen has got into the range, its temperature will stay nearly

constant for some time in spite of the inevitable leakage of heat into it from the surroundings. The barrier temperature can be lowered by taking a more dilute crystal, for example by mixing the iron alum with some non-magnetic alum, but the process will break down in the same sort of way that we saw occurred in the production of cold by vapours. The diluted crystal will have fewer little magnets available for giving up their energy, and so we should have to take a larger specimen or use a stronger magnet in order to get even the same temperature-drop. To get much below 0.003°K , we should therefore have to take a great bulk of inefficient material in a strong magnetic field (and of course in a vacuum), and it simply cannot be done technically. The method of demagnetization by means of paramagnetism is exhausted at somewhere a little above a thousandth of a degree.

NUCLEAR REFRIGERATION

This is more or less how matters stand now, but it is not necessarily the end. Not long after the magnetic method had been shown to work it was suggested that it would be possible to get a similar process starting at the present lowest temperature and going down again by the same sort of factor to something near a millionth of a degree. The effective system was to be the magnetism in the nucleus of the atom. A good many atoms have magnetic nuclei, and their strengths are about a thousandth of those we have been discussing, and this is exactly what is wanted. The proposal was to take a diamagnetic salt of a metal of this character and work with that. The experiment was not going to be easy, because it was necessary to cool this specimen to 0.001°K in a magnetic field by contact with a paramagnetic which had already been cooled so far by being taken out of the field; for this a long heat-conducting channel would be essential, and this channel, probably of liquid helium, must itself also be lowered to the same temperature.

Theory, however, suggested a curious difficulty. For the process to work, it is not sufficient merely to get the energy out of the magnets, but these magnets must also be able to borrow the energy from the rest of the system so as to restore equipartition; for if they do not, we cannot say the temperature has really been lowered. It is true that at this stage there is hardly any energy left except in the magnets themselves, but still there is some, and unless the right proportion of this is duly borrowed to restore equipartition we cannot say that the temperature has really been lowered—for example, we could not chill a second body by placing it in contact. Now theory shows that the rate of this borrowing will depend enormously on the temperature. At 1° it is instantaneous, at a thousandth it takes seconds or minutes, but at a millionth it may easily take a million years. The heat insulation has so to speak become so good that different parts of the same molecule can be at different temperatures for a million years without the heat flowing from one to the other. But the same work that revealed this difficulty showed a way out. The structure of a metal is very different from that of a salt, in that, however low the temperature, there are always electrons moving about in it at high speeds—this does not contradict equipartition, but I must take that for granted. These electrons act as middlemen and succeed in bringing about equipartition

quite rapidly. So it seems likely that perhaps in a few years, by the use of a metal in which the nuclei have a magnetic moment, it may be possible to reach temperatures down to perhaps a hundred-thousandth, perhaps a millionth, of a degree.

What will be the properties of matter there? Frankly, I do not think it likely that they will be very sensationally different from those already found at a thousandth. There are a few things we should like to know—for example, whether other metals become superconductors besides those already found at 1° . It would also be interesting to know whether the paramagnetics become permanent magnets, though I doubt whether that is feasible because of the slow rate they would have in coming to equipartition with the cold body. But Simon has suggested another more remarkable idea about such temperatures, and this is that the whole idea of temperature itself fades away.

For temperature to have a practical meaning one must be able to take the temperature of a body with a thermometer. Now this implies that the thermometer must be smaller than the body of which it is measuring the temperature, for otherwise it will itself disturb the body's heat. But there is now so little energy in the whole body that most of the time the thermometer will have none at all, and then occasionally it will have much too much. To understand why this is so, I may return to my metaphor of the doctors. The town is now so poor that its total capital only amounts to a few of the cheapest doctors' fees. Most of the time nobody has enough money to pay a fee, but occasionally someone scrapes enough together and consults a doctor. Obviously, we shall get a very different account of the health of the community according to whether we ask the fortunate doctor who has just got a fee, or one of the other members of his profession. The indefiniteness is, however, a matter of size. If we consider the health of a much larger town, or of a whole country, we shall find that there are a good many doctors who have got fees, and by averaging

over them we could get an idea of the health of the community. So if we want to speak *usefully* of temperature at these very low temperatures we must take a large body, and the colder the temperature the larger the body must be. Actually this region of indefiniteness is even now not at all far off. The first substance to show the effect would be a diamond, and it can be shown that a grain of diamond dust which is just visible will have a quite indefinite temperature at the temperatures already reached.

We seem to be ending on an anticlimax. Each successive stage in producing cold has called for greater efforts and has on the whole produced less results. In the first stage we leave all the rich variety of physical and chemical activity of ordinary temperatures—incidentally, the activity that makes life possible—for the austere region of liquid helium. Here we have lost all chemistry, and have only found as compensation the interesting phenomenon of diminished specific heats and the startling fact of superconductivity. In the second stage of paramagnetic demagnetization there seems even less novelty, and the chief interest is in whether things will become permanent magnets. In the third stage of nuclear demagnetization we cannot know what will happen, for it still lies in the future, but the most likely thing is that the target we are aiming at will simply fade away into indefiniteness before us. To anyone who asks whether the journey is worth while I would answer—is climbing a mountain worth while? In the first stage we leave the rich fertility of the plains for the rocks and glaciers of the mountain; we lose a great deal, but gain one new thing, perpetual snow. In the second stage we ascend to the top of Everest; the change is less than in the first, but we encounter the new difficulty of shortage of oxygen and the terrible winds of the heights. In the third stage we are to ascend into the stratosphere and to discover the still sparser problems that remain, concerning the character of the upper air. I hope that you will agree with me that these journeyings are well worth the while.

INSULATION

By H. WARREN, Member.*

(ABSTRACT of Lecture delivered before the METER AND INSTRUMENT SECTION, 3rd May, 1940.)

INTRODUCTION

An insulating sheath may contain a high-voltage, high-temperature conductor, which is elongating and contracting, vibrating and hammering inside the sheath, whilst a hot, wet or corrosive atmosphere is assailing its outside. The sheath should have the stability of a granite cliff and the adaptability of india rubber, oil or brown paper. As a matter of fact, insulations are made of such things, but literally in many thousands of variations of these mineral, gummy, oily or cellulose substances.

Insulation is, of course, an art, including the many intricate applications and treatments of certain materials in film-forming, cementing, sealing, impregnating, filling and moulding processes. It must include also the study of dielectric phenomena. I propose for the most part to discuss a few disjointed examples of the influence of researches and applications which are at the moment in progress, on the advance of the art in general.

SYNTHETIC-RESIN MOULDINGS

The period from Baekeland's classical invention of 1908 to the year 1940, and especially the more recent years, has been prolific as regards the evolution of interesting synthetic insulating products. Table 1 summarizes some outstanding classes of materials, and I introduce it because the middle column reveals how the chemists have been working with a few elements and simple groups which, like the fragments in a kaleidoscope, combine over and over again into an endless variety of balanced structures.

The question may well be asked: What has the electrical industry done about synthetic-resin mouldings during the last 20 years? The answer is that it has helped to develop, and has used, a wide range of products, but the phenolic-formaldehyde compounds remain in the forefront in electrical applications; they have been made better, more uniform, more adaptable and far cheaper.

I well remember the time when we were taking 30 minutes to mould and 24 hours to cure hard-rubber radio parts, which had afterwards to be straightened, machined and polished; usually one-third of the mild-steel moulds were in the tool-room under repair. Then came rudimentary but expensive synthetic material from which we moulded the parts in 10 minutes, and when they did not stick in the moulds we had only to buff off the flash lines and polish up the surfaces. Now, similar parts are moulded in 3 minutes in easily operable durable hard-steel moulds which impart such a beautiful finish to the mouldings that polishing would spoil them. The cost of the present synthetic compound is less than one-quarter that of the material of 20 years ago.

* British Thomson-Houston Co., Ltd.

The modern phenolic-formaldehyde compounds have excellent electrical, mechanical and physical properties; indeed, in power-frequency applications they have only one remaining defect. The risk of surface carbonization under the influence of an arc or a spark has never been entirely eliminated. This is not because the problem has escaped attention, but because of its great difficulty. Considerable progress has been made, and I propose to describe some of the interesting work that has been done on the subject in the laboratory with which I am connected.

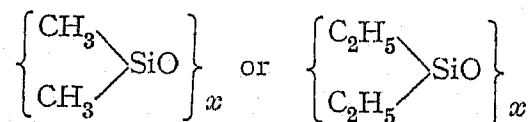
SURFACE CARBONIZATION, OR "TRACKING"

Watch how a sample of normal phenolic-formaldehyde wood-filled compound behaves when a substantially unidirectional spark is drawn across its surface. After a little while, a bright spot of incandescent material appears under the cathode and gradually moves across to the anode, leaving a low-resistance conducting path of carbon behind. The spark has disappeared, for this carbon "track" now conducts the current from one electrode to the other, and the insulation has been destroyed in about 30 seconds.

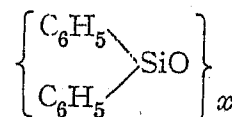
In practice, all mouldings and high-voltage inserts must be so designed as to eliminate all possibility of electrical discharges occurring near the compound surface.

Certain ignition apparatus, used, for example, on important petrol engines, has now to operate at such high temperatures that hard-rubber mouldings—formerly used because of their excellent electrical and non-tracking characteristics—have too low a plastic yield. Phenolic-formaldehyde mouldings which have been rendered anti-tracking are at present the only solution. The problem has become of special importance.

The "tracking" tendency of the moulded material appears to be associated with the proximity of a phenyl (C_6H_5) nucleus, and this view receives some substantiation from a silicon organic-compound analogy. Thus, whilst the di-methyl or di-ethyl silicone polymers



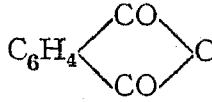
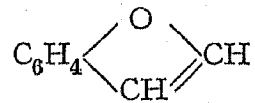
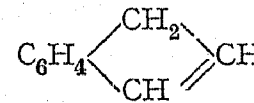
have good tracking resistance, the di-phenyl silicone polymer



tracks very readily indeed. This fact casts strong suspicion on the C_6H_5 with its rich carbon content.

In general experience, resins which contain a pre-

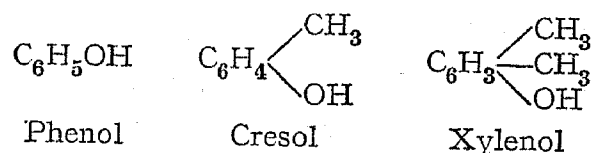
Table 1

Resin types	Formulae of basic materials	Trade names
Phenol-aldehyde	C_6H_5OH Phenol $C_6H_4(CH_3)OH$ Cresol $C_6H_3(CH_3)_2OH$ Xylenol HCHO Formaldehyde	Bakelite, Mouldrite, Nestorite, Rockite, Fabrolite
Urea - formaldehyde and thio-urea formaldehyde	O : $C(NH_2)_2$ Urea S : $C(NH_2)_2$ Thio-urea HCHO Formaldehyde	Beetle, Mouldrite, Scarab
Alkyd resins	$CH_2OH.CH_2OH$ Ethylene glycol $CH_2OH.CHOH.CH_2OH$ Glycerol  Phthalic anhydride	Glyptal
Aniline-formaldehyde	$C_6H_5.NH_2$ Aniline HCHO Formaldehyde	Panilax
Polyacrylic	$CH_2 : CH.CO_2CH_3$ Methyl acrylate $CH_2 : C(CH_3).CO_2CH_3$ Methyl methacrylate	Diakon, Perspex
Polyvinyl	$CH_2 : CHCl$ Vinyl chloride $CH_3.CO.O.CH : CH_2$ Vinyl acetate	Flamenol, Victrol, Gelva, Alvar, Formvar
Polystyrene	$CH_2 : CH.C_6H_5$ Styrene (i.e. phenyl ethylene)	Trolitul, Distrine, Styroflex
Polyethylene	$CH_2 : CH_2$ Ethylene	Polythene
Phenol-glycerol	C_6H_5OH Phenol $CH_2OH.CHOH.CH_2OH$ Glycerol	Acrolite
Aniline-butyraldehyde	$C_6H_5.NH_2$ Aniline $C_3H_7.CHO$ Butyraldehyde	Bentene
Resorcinol-trioxymethylene	m- $C_6H_4(OH)_2$ Resorcinol $(HCHO)_3$ Trioxymethylene	Bimolithe, Bincolite, Novoresit
Resorcinol-formaldehyde	m- $C_6H_4(OH)_2$ Resorcinol HCHO Formaldehyde	Durium
Aniline-heptaldehyde	$C_6H_5.NH_2$ Aniline $C_6H_{13}.CHO$ Heptaldehyde	Heptene base
Coumarone and Indene polymers	 Coumarone  Indene	Cumar, Para coumarone, Neville resin
Synthetic rubbers	$CH_2 : CH.CH : CH_2$ Buta-diene $CH_2 : CCl.CH : CH_2$ Chloroprene (Beta-chlor-butadiene)	Neoprene (chloroprene polymer)

dominance of alkyl groups, such as the urea-formaldehyde or glyptal resins, show little tendency to track, and in this particular respect they are superior to phenolic-formaldehyde products.

The glyptal resins contain a lower percentage of carbon and a higher percentage of oxygen than the phenolic-formaldehyde resins, and are thus less likely to deposit a copious free-carbon track. As common phenolic-formaldehyde moulding compositions consist essentially of the resin mixed with wood flour, the problem of overcoming the tracking difficulty resolves itself into considering what useful modifications can be made either to the resin or to the filler, or what advantage can be gained by dilution with other materials, known to be non-tracking and non-inflammable.

As regards modifying the resin itself, the progressive substitution of alkyl groups (CH_3 , C_2H_5 , etc.) for hydrogen in the nucleus of phenol effects some improvement in arc resistance, but this advantage is unfortunately offset by a lowering of the reactivity and thermo-rigidity of the resulting moulding compound. In this connection there has been careful study of the tracking behaviour of the resins prepared from phenol, cresol and xyleneol, which are nicely graded as regards the introduction of alkyl (CH_3) groups into the C_6H_5 nucleus, so:



The differences in the tracking behaviour of these neat resins are not at all definitely marked, but there are the expected differences in the behaviour of moulding compositions produced therefrom—accompanied, unfortunately, by lengthening of moulding time.

As regards varying the cellulose filler, there appears to be little difference in the tracking tendency of various wood-flours or other cellulose fibres so far examined. Any improvements which have been made in this connection are of a minor nature. It is interesting to note that wood-flour which has been liberally treated with fire-proofing reagents tracks just as badly as untreated wood-flour.

The possibility of reducing the tracking tendency by the addition of various non-tracking resinous diluents has been carefully investigated, but even substantial additions fail to improve matters materially. Some considerable measure of success has been achieved by a partial substitution of the vegetable filler by mineral filler, e.g. talc, silica, mica or asbestos. Probably the mineral filler acts as an inert diluent, dispersing the organic resin, allowing more complete combustion of that on the surface and protecting that beneath. Of course, mineral dilution reduces the overall carbon content.

It must be appreciated that a modification of this type does not produce a "non-tracking" compound equal to hard rubber in this respect; indeed, we only call it *anti-tracking*. A compound with the following ideal requirements is still being earnestly sought: (a) High electric and mechanical strength. (b) High thermal rigidity and dimensional stability. (c) Good water resistance. (d) Non-tracking properties. (e) Rapid curing speed and accurate and fine moulding finish, with a flexible adapt-

ability for a wide range of moulding and machining conditions. (f) Cheapness and consistency in manufacture.

It can, however, be said that the mineral-filled phenolic compounds approximate more closely to this ideal at the moment than any of their rivals, and this class of compound is therefore finding a useful and important application. Certain characteristics of such a mineral-filled compound, as compared with similar wood-filled material and with hard rubber, are given in Table 2.

The sacrifice of mechanical strength will be noted, and it may be mentioned that the avoidance of greater sacrifice and of unduly reduced "mouldability" have been amongst the major difficulties of the work.

If the tracking experiment described above is per-

Table 2

	Wood-filled compound	Anti-tracking mineral-filled compound	Hard rubber compound
Loss factor at 20° C. . .	1	1	0.038
Rapidly-applied-voltage breakdown voltage (½-in. disc at 70° C.), volts per mil . .	250	250	500
Cross-breaking strength, lb. per sq. in. . .	10 000	6 500	8 000
Plastic yield, ° C. . .	170	150	80
Relative moulding time	10	10	15
Tracks	Easily	With difficulty	Non-tracking

formed on a piece of the new mineral-filled compound, it is found that the same spark does not damage the material even if it is left playing for several minutes.

THE PHYSICAL ASPECT OF "TRACKING"

The purely physical aspect of the "tracking" phenomenon is of interest, and in the usual tracking test it seems that the mechanism is as follows: The cathode region of the arc hugs the surface of the compound, but the positive column rises from the surface to avoid cooling, which would raise the voltage gradient. The cathode spot is thus at the tip of the negative electrode, and the anode spot is near the tip of the positive electrode. The material under the cathode is bombarded by electrons, and is heated and decomposed. Some carbon remains, and as it were extends the cathode a little closer to the anode. This carbon cathode spot heats the adjacent material, thus forming another cathode spot a little closer still to the anode. In this way the carbon spot, connected by a carbon track to the cathode, progresses, ultimately reaches the anode, and bridges the gap with a conducting carbon path. The track always starts from the cathode, for, although the heating of the

anode is greater, the anode spot is on the metal electrode, a little above the compound.

Reversing the polarity after the track has started produces a curious effect. If, when the left-hand electrode has been the cathode and the track has progressed a little, the polarity is reversed, a fresh track starts from the new cathode on the right. The old track, however, also progresses even more rapidly than before. This is because the spots in the compound are now acting as anode and cathode, and the heating of the anode is greater than that of the cathode. Tracks progress from either electrode more readily than they will start; thus breakdown of a considerable length of phenolic-formaldehyde surface may be delayed, but once it commences there is very rapid failure.

NEWER SYNTHETIC RESINS

Apart from the common synthetic resins such as those of the phenolic-formaldehyde, urea-formaldehyde and glyptal classes, a number of most interesting polymerization products have arisen during the past few years. I will mention the polyacrylic, polyvinyl, polystyrene and polyethylene products, the chemical appearance and ancestry of which are given in Table 1.

The polyacrylic resins are notable for their colour-free transparency and adhesiveness. They have accordingly found application in the manufacture of laminated glass and, more recently, the harder polymethyl methacrylate has been used for lens manufacture and other optical purposes. These polymers have good electrical properties and good resistance to water, petrol and mineral oils, and approximate to cellulose acetate as regards non-inflammability.

Polyvinyl chlorides — typified by Flamenol — are flexible, inert and non-inflammable materials with remarkably good ageing properties, and are mainly used as low-voltage cable coverings. Straight polyvinyl acetates are marketed under the name "Gelva." They possess very good ageing properties and adhesiveness, and their electrical properties are also good. They are not, however, particularly resistant to water, acids and alkalis. A modification known as Formvar is obtained by reacting the hydrolysed Gelva with formaldehyde. Formvar has improved softening point, solution viscosity and mechanical strength, and recently has found an important application in the formulation of Formex wire enamel, which is so tough that in many applications the cotton covering on enamelled wire can be dispensed with.

The polystyrenes are particularly suitable for injection moulding; they are inert and do not absorb water. Their softening point is somewhat low. Their high electric strength and low power factor render them especially suitable for high-frequency applications, in which connection they are to be mentioned later.

The polyethylene products are tough, horn-like materials and have good electrical properties. They can be moulded, extruded or cast, and can also be converted into films and tapes.

THERMO-SETTING VARNISHES, ETC.

Those engineers who are interested in eliminating production troubles associated with varnish or japan throwing, will find thermo-setting varnishes to be of consider-

able assistance. "Throwing" or "slinging" usually occurs on test, when small or large high-speed rotating members are apt to throw out appreciable quantities of liquid varnish. Hitherto, despite rigid control of the treatment process, it has only been possible at the best to minimize the trouble. Its primary cause is that the varnish used contains drying oils such as linseed oil. This varnish accumulates in pockets in the rotating part, and, whilst baking forms a hard surface skin, liquid varnish underneath remains liquid. This liquid varnish cannot harden, because oxygen is necessary to solidify its drying oil, and the impervious surface film excludes this oxygen. Hence if a varnish can be obtained the base of which can be solidified by heat alone, the difficulty of hardening accumulations of varnish right through is at once overcome. Although varnishes of the phenolic-formaldehyde type will do this very readily, it has been found in practice that best results are obtained with a varnish which consists of thermo-setting resins carefully blended with thermo-setting drying oils, e.g. china-wood oil. A varnish of this type that has been developed lately is a blended xylenol-formaldehyde and china-wood oil composition.

Coils can now be impregnated completely, and all cavities filled, by applying a solventless synthetic-resin varnish base which hardens throughout. In some experiments on this material two test tubes containing the same amounts of normal yellow impregnating varnish and of this solventless base were baked under the same conditions. At the end of the experiment the normal varnish was found to be considerably shrunk and still liquid beneath the surface skin, whereas the other was solid throughout. The usefulness of this property is illustrated in Fig. 1. A solid filling with special resin is an effective solution of the problem of eliminating corona in high-voltage coils operating at reduced air pressures.

CHLORINATED DIPHENYLS

The adoption of mineral oils for insulating and cooling transformers, etc., was a major development in electrical engineering. These hydrocarbon oils, however, have disadvantages as regards inflammability, sludging and the explosive nature of arc-formed gases.

It had long been known that the combustibility of many organic compounds is reduced by the substitution of chlorine for hydrogen in their molecules, and that some of the non-inflammable halogenated hydrocarbon compounds are good insulators and are stable; such materials were, however, laboratory products and it was not until diphenyl became available commercially that the use of its chlorinated derivatives for insulation purposes became a practical proposition.

Such derivatives are prepared by the direct chlorination of diphenyl; the products are fractionally distilled and separated into groups according to the degree of chlorination. Thus they are usually specified in terms of distillation range and chlorine content; the liquid products in general boil between 300° C. and 400° C., and have a specific gravity of about 1.5. Chlorinated diphenyls are known in this country, in America and in Germany respectively as Permitol, Pyranol and Clophen. As the degree of chlorination increases, the viscosity tends to increase and the solvent action to decrease, and for

transformer applications it is necessary to combine low viscosity (for cooling) with low solvent activity. These conditions are met by mixing 60 % of hexachlor diphenyl with 40 % by volume of trichlor benzene. The mixture has a permittivity of about 4, as compared with 2 in the case of transformer oil. Thus the permittivity is similar to that of the associated solid insulators (impregnated papers, woods, shellac-bonded products, etc.), and this enables a more uniform distribution of electric stress to be obtained in the insulation. The liquid has a breakdown strength similar to that of oil, it is non-sludging and non-flammable, and any gases formed as the result of arcing are non-explosive.

Since Permitol compositions are inherently more expensive than transformer oils, when the former are used it is necessary to design the tanks and cooling systems with special regard to economy of fluid.

synthetic resinous and ceramic compositions of greatly improved characteristics have in recent years been introduced. They may be summarized under the following headings: wood, hard rubber, synthetic resins, mica and mica-glass, quartz and ceramics. The power-factor and permittivity figures given in Table 3 illustrate, in particular, the great advances for which synthetic-resin and ceramic researches have been responsible. There are, of course, a good many high-frequency applications in which glass is employed, but I propose to deal with glass on a slightly broader basis.

NEW APPLICATIONS OF GLASS

In recent years, glass for insulation has perhaps received most concentrated attention in connection with woven products and wire insulation, and in connection with the construction of vacuum devices where insulation

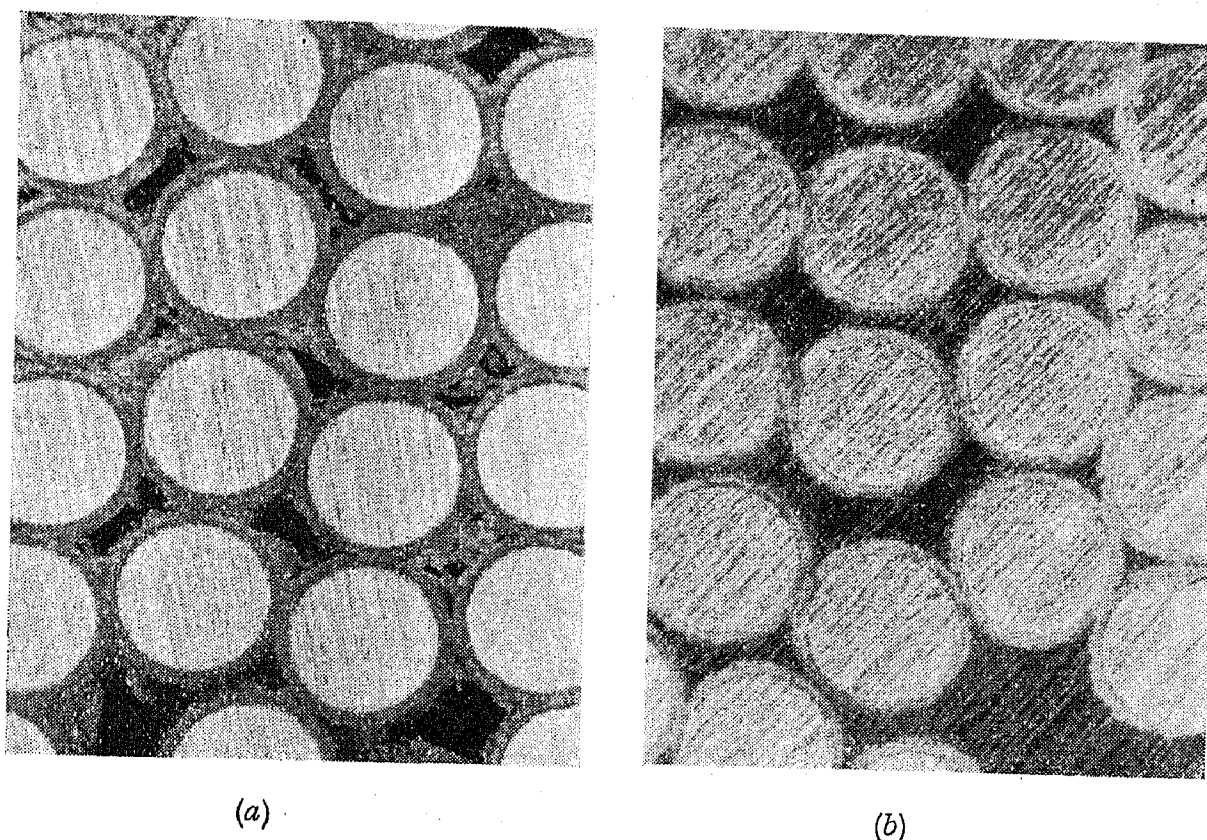


Fig. 1.—Photographs of sections of cotton-covered wire coils (magnification, 10).
(a) Impregnated with oil varnish. (Note unfilled spaces between wires.)
(b) Impregnated with oleo-synthetic resin. (Note complete filling of spaces between wires.)

As regards condenser applications, the high permittivity of chlorinated diphenyl, together with its ability to work stably at a higher electric stress than other impregnants, render it eminently suitable, for example, for use as an impregnating medium for paper condensers. Permittol can be produced in a form suitable for condenser impregnation with a permittivity in the neighbourhood of 5. Permittol in the form of impregnated paper, or of Kraft condenser tissue, has a permittivity of 6.

Chlorinated diphenyls are not generally suitable for switchgear applications, because of the liability of objectionable dissociation products being formed in the main arc-rupturing and isolator chambers.

HIGH-FREQUENCY INSULATING MATERIALS

Radio apparatus for communication and for all the peculiar purposes of these days utilizes a group of specially selected low-loss materials, and remarkable

characteristics have to be combined with very special chemical and physical properties.

Woven Glass, and Glass Insulation for Wires

The general prospect of home-producible controllable fibres for non-inflammable acidproof textiles that will not mildew or rot is certainly inviting, and as far as insulations are concerned attractive preliminary products have been available for some time.

The electrically melted alkali-free glass is drawn over revolving drums as extremely fine fibres of approximately 0.0002 in. diameter, and the spun yarns produced are consequently soft and flexible. Except for a small amount of lubricant, the yarns are entirely composed of glass. The tapes are uniformly woven, smooth and free from nap. They have high tensile strength, withstand temperatures higher than those met by standard Class B insulation, and when properly impregnated have good

electrical properties and moisture-resistance. Tapes are available 3.5 mils thick, and these are thinner than normal asbestos tapes. This property, together with the high tensile strength, enables taping to be tight and compact.

These materials are particularly attractive for the insulation of conductors designed to resist high temperatures and corrosive atmospheres. A recent series of tests indicate that glass-covered wire has better electrical properties than asbestos-covered wire under high-tempera-

Table 3

INSULATING MATERIALS FOR HIGH-FREQUENCY APPLICATIONS. TYPICAL POWER-FACTOR AND PERMITTIVITY VALUES FOR VARIOUS GROUPS.

FREQUENCY, 1 000 KC./S. TEMPERATURE, 20° C.

Group	Power factor (tan δ)	Permittivity	Examples
Wood	0.036	2.9	American white-wood
Hard rubber (unloaded)	0.0095	2.8	Ebonite
Hard rubber (loaded)	0.01–0.035	2.5–4.5	Silvonite Keramot Stabalite
Synthetic resins	0.022	2.8	H.F. bakelite
	0.011	3.7	Panilax resin
	0.0004–0.00045	2.1–2.3	(Trolitul, Distrene, Styroflex)
Mica	0.00018	7.0	—
Mica-glass	0.002	7.5	Mycalex
Quartz	0.0001	4.7	—
Ceramics, etc.	0.0063	5.4	Porcelain
	0.002	6.5	Steatite
	0.00025–0.00035	6.0–6.5	(Frequentia, Calit, Calan)
Rutile bodies	0.0003–0.0006	40–80	(Condensa, Faradex, Tempa, Kerefara)

ture or moist conditions. The glass covering has a superior space factor and is fairly robust, but it is necessary to study the bonding of the smooth elastic fibres in the covering and their anchorage on the conductor, having regard to the liability of displacement in the shop handling operations. Coverings must therefore be impregnated, and the characteristic weakness in shear has to be considered in reference to abrasion resistance.

A standard 10-h.p. induction motor was insulated

throughout with glass insulation and the indications were that glass-insulated motors would probably be suitable for continuous working temperatures approaching 200° C.

Glass for Vacuum Devices

One of the most striking developments in this field has been the production of glasses for the inner bulbs of mercury discharge lamps. Here the conditions are so severe that all normal glasses, including boro-silicate glasses of the Pyrex type, are unsuitable. Glass intended for use at a temperature well above 600° C. must possess high electrical resistivity, resist electrolysis and withstand the chemical effects of the mercury discharge. A further requirement is that its ultra-violet transmission must be high.

Glasses with high softening-points and high electrical resistivity at high temperatures must necessarily have a

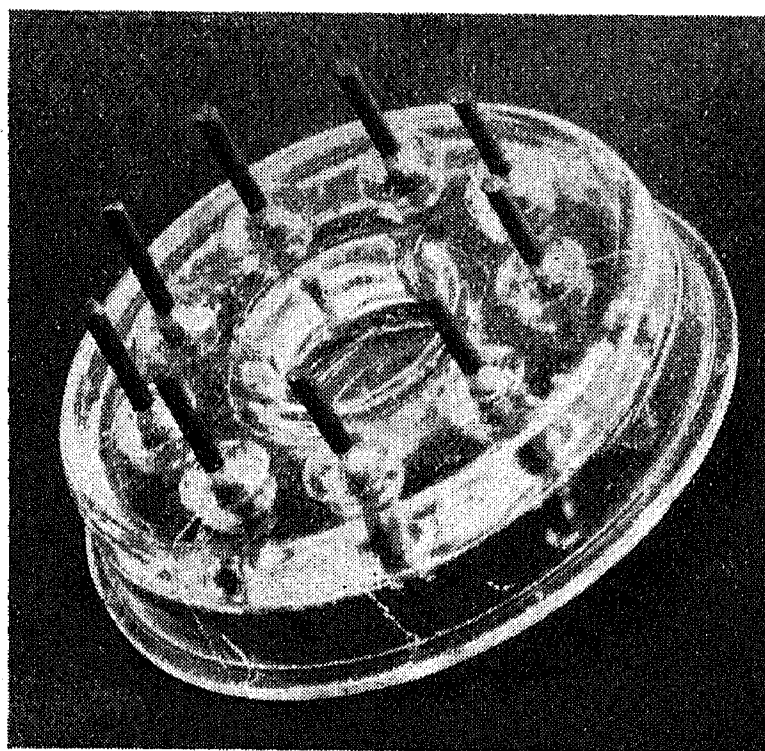


Fig. 2.—Glass valve base.

very low alkali content, and the new glasses conform to this requirement and contain a high percentage of alumina. Ultra-violet transmission demands less than 0.05 % iron-oxide content. A typical glass contains approximately 55 % silica, 25 % alumina, and small percentages of lime, baryta and boric oxide.

In glass for the manufacture of sodium discharge lamps, high electrical properties at about 300° C. have to be combined with resistance to sodium-vapour attack. To achieve this the glass must have low silica content together with the least possible iron-oxide inclusion, and for this reason it is preferably melted in a platinum pot. A typical composition is 32 % baryta, 30 % boric oxide, 25 % alumina and a little soda and potash. Such glass, however, is far too soft to be used in the form of tubing, and it is therefore necessary to "case" it with soda-lime glass having an exactly corresponding expansion coefficient.

Amongst the more impressive applications of glasses in electrical apparatus may be mentioned the bulbs for large

mercury-pool rectifiers and for large television cathode-ray tubes. Both these glasses are boro-silicates with a high silica content and usually some 15 % of boric oxide. A recent requirement is pressed-glass bases for high-frequency radio valves, and glasses of compositions similar to the foregoing have been developed for the purpose. Power factors as low as 0.0006 and permittivities of 4.2 are attainable.

Fig. 2 is a photograph of a recently-made glass valve-base with moulded-in connecting pins.

Many different glasses transmitting and absorbing selected wavelengths have had to be developed for special purposes. The glassworks of one large electrical concern has in regular large-scale production more than 20 standard glasses and many more special glasses.

The smallest glass-insulated and glass-enveloped device regularly made is so minute, and the largest is so huge, that half a million of the former could be contained in the latter.

INSULATING PROCESSES

Many applications and treatments of insulation materials are necessary to get them into the desired condition, form or place. In many of these operations pressure and heat have to be employed. I should like to refer to a new method of pressing and to a relatively new method of heating.

A New Method of Pressing Insulations on Coils, etc.

It has been common practice, almost since the earliest days of electrical manufacture, to wrap and hot-press insulating materials, such as treated papers, fabrics and micanite, around conductors. This has been a convenient process where the parts to be pressed were of such simple form that pressing plates or simple moulds could be employed. It has been impracticable generally to press insulation on to complex coils or the bent portions (evolutes, etc.) of machine windings and field coils, because of the necessity of intricate and expensive moulds.

A method of pressing and moulding has been developed recently* which largely overcomes this difficulty. The process consists of applying pressure by means of hot steel shot. For example, a coil which requires an insulating covering of synthetic-resin-treated fabric is covered with the material and then served with india-rubber tape. It is then placed in a strong steel box provided with a plunger forming the lid, the space around the coil being filled with steel shot previously heated to a temperature of, say, 150° C. Pressure is applied to the plunger, and is transmitted by the steel shot in all directions, so that all the surfaces of the coil are pressed. After the requisite period under heat and pressure, the shot is poured out, the coil is extracted, and the rubber tape is removed. The rubber is, of course, employed to prevent the shot from adhering to the insulation being pressed.

Insulating coatings can be pressed in a similar manner on to quite small coils, on to conductors, busbars, etc., of various shapes, and insulating linings can be moulded to the insides of metal boxes by reversing the arrangement and applying pressure to steel shot filling the space inside the boxes. One peculiar advantage of this method

is that the pressure follows up any irregularities of the surfaces being pressed, a feature which cannot usually be ensured with rigid moulds. Apart from the obvious economy of not having to make expensive moulds in which to press articles of which only a few may be wanted, the time required to make the moulds is eliminated, and this feature is often of vital importance in urgent experimental work or repairs. Examples of the use of this method for pressing insulation on to coils, also for moulding a box or a lining inside a box-like container, are illustrated in Fig. 3; and photographs of typical coils, etc.,

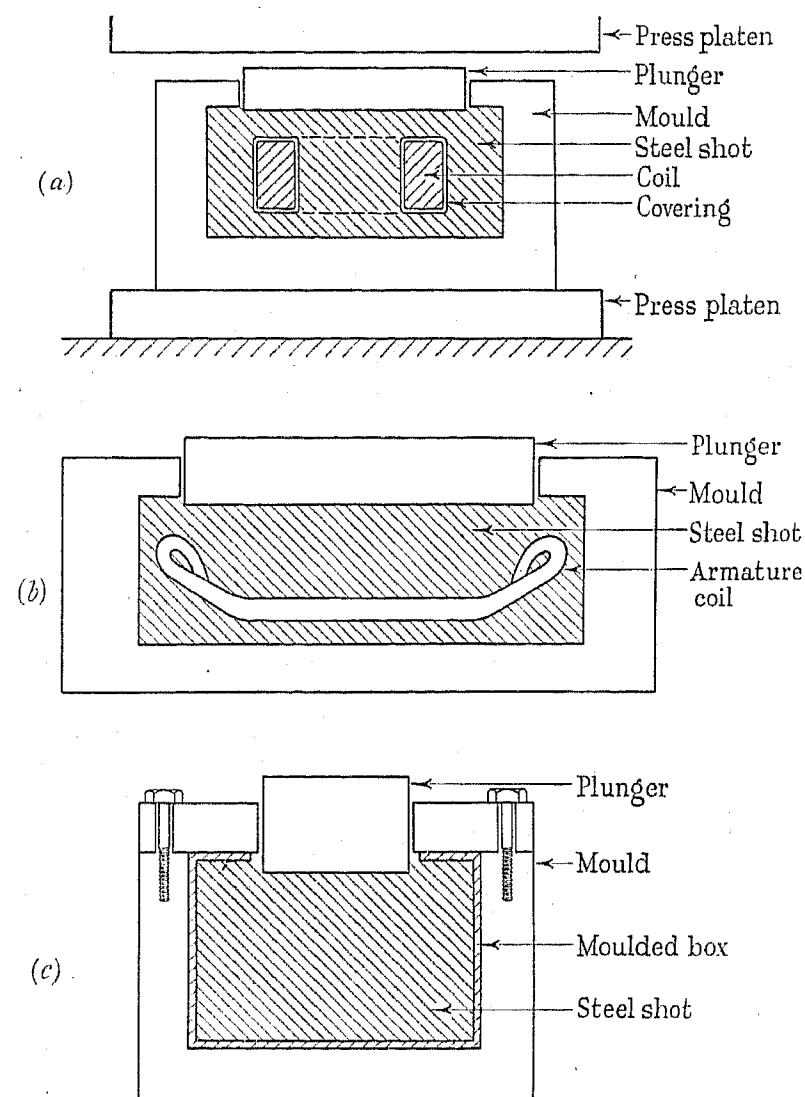


Fig. 3.—Slot moulding process.

- (a) Moulding a coil.
- (b) Moulding an armature coil.
- (c) Moulding a hollow box.

insulated or made by this process are reproduced in Fig. 4. This method has already been used for pressing objects of size ranging from less than 1 in. to over 9 ft. long.

A Method of Hardening Films by Radiant Heat

Considerable attention has been devoted to the claims that synthetic enamel and varnish protective films may be hardened with improved efficiency by means of radiant heat. The matter is, of course, of interest in the case of insulating films.

It has been established by original work in the Ford factories that motor-car bodies can be stoved in considerably less time when the ovens are equipped with batteries of electric lamps instead of conventional heat sources. It has been claimed that the infra-red radiation

* British Patent No. 401276—1933.

has a deep heating effect accelerating the hardening of the films, and a considerable series of experiments has been made on this subject from the insulation and protective-coating points of view, and to determine the conditions under which a film may in fact be hardened satisfactorily in 5-7 minutes.

Tungsten-filament lamps under-run at relatively low colour temperature give long life and the best balance of penetration and absorption. The best reflecting surface for directing infra-red energy upon the job under treatment is gold plate, and next come copper and silver.

As far as we have been able to ascertain at present, if the temperature of the particular protective films tested can be raised to about 400-450° F., either by lamp radiation or by less convenient means, the films can indeed be satisfactorily hardened in some 5-7 minutes, instead of in 60 minutes at 260° F. At these high temperatures

engineer draws his materials from the rocks, the soil, and the laboratory of the synthetic chemist. He fashions and applies them with the ancient arts of the potter, the glass-maker, the weaver and the embalmer; some of his processes he has even invented himself.

The electrical engineer faces stresses which he must trust his insulations to bear, he braves corrosive attacks from which insulations must protect. His designs in metal give life to his creations; his non-metallic "details," be they oil in the bearings or wrappings on the coils, endow his creations with long life. For enhanced performance, a prime requirement is better insulation: insulation that is stronger, more adaptable and more enduring.

In visualizing these advances, and pursuing their realization, even greater originality and boldness of approach may be possible along certain lines. The

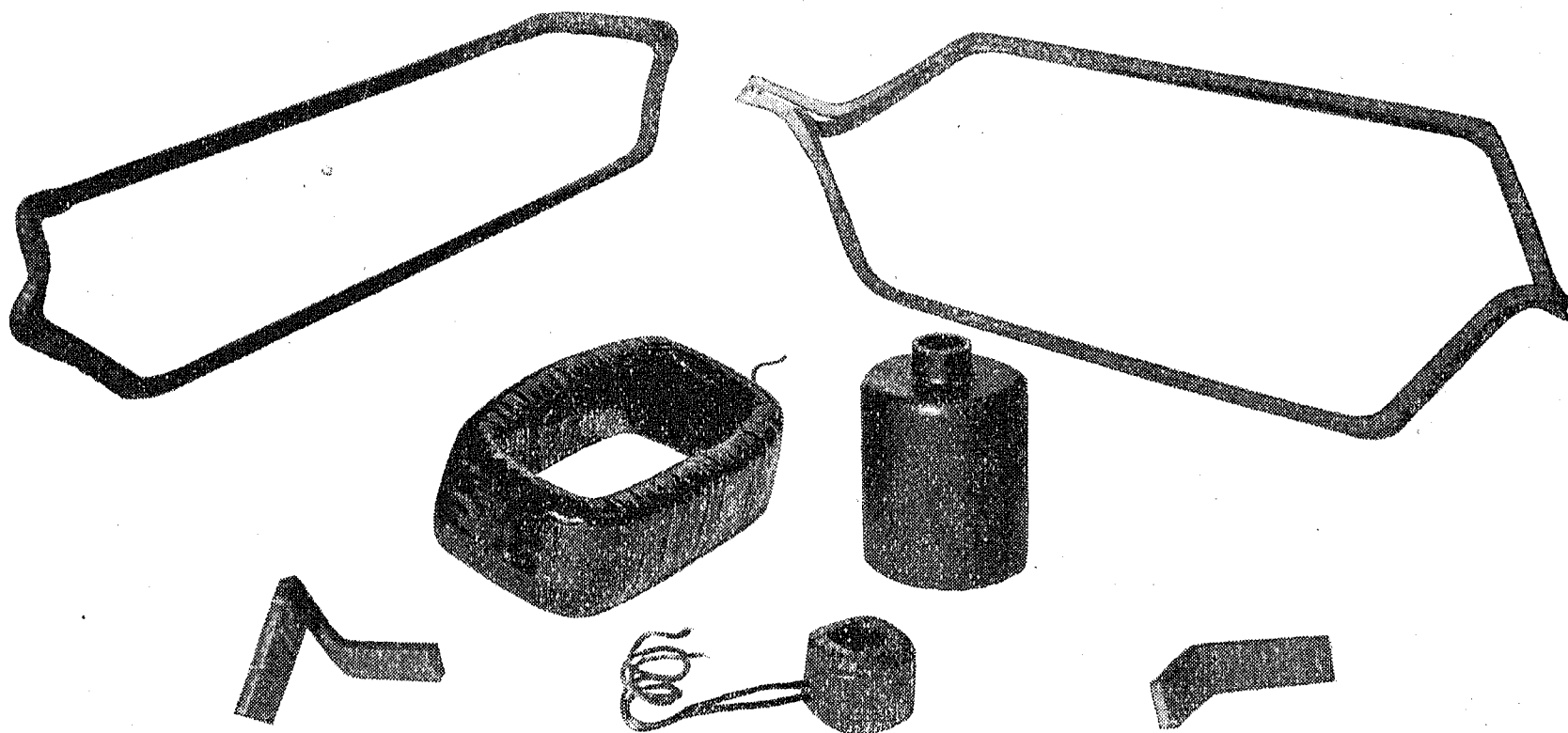


Fig. 4.—Shot moulding process: typical mouldings.

there is, of course, obvious danger of discoloration with light-coloured finishes, together with some tendency to blistering. From the tests made, it appears that the radiant heating method has advantages in those cases where it is desired quickly to concentrate heat locally on treated surfaces, and where it is impracticable or wasteful to raise the whole assembly to the maximum stoving temperature required for rapid hardening of the surface. The system of lamp baking appears to be a means of heating which, in many cases, will be more convenient than the methods usually adopted. The heat can be directed, with little thermal inertia, efficiently on to the required area, instead of being diffused as in ordinary oven baking.

INSULATION PRACTICE

The insulation engineer is largely a material-monger. In, on and between his wares there are immersed, wrapped, supported or separated the conductors contrived by the *real* electrical engineers. The insulation

organic chemists have already been brilliantly conspicuous in their syntheses of resinous bodies. There have been far-reaching advances in the improvement and development of new organic textiles; glass textiles even threaten the pre-eminent heat resistance of asbestos in certain electrical applications. Why not study, for example, the further possibilities of thin, flexible glass films as well as fibres, the synthesis of mica or the welding-together of natural mica flakes into continuous flexible tape? The resources and achievements of modern experimental research encourage one not to regard as impossible the establishment, at least in the laboratory, of the temperature and pressure or bonding conditions under which mica crystals might be studied and manipulated profitably. We have already the excellent mica-glass agglomerate, Mycalex, and mica flakes have been quite commonly bonded with organic and inorganic cements (without paper or other flexible backing) into flexible sheets and tapes.

The welding or growth of mica crystals seems rather

an ambitious interference in the concerns of nature, but we are growing in the laboratory rochelle-salt crystals in unnatural thin flat plates because we want them in this form for piezo-electric units; and tungsten crystals are grown in considerable lengths because we need them in the form of wire for lamp filaments. When we think of such curious achievements as organic water jaspers, the etching of glass bulbs which makes them stronger, the manufacture of luminescent powders which involves super-purification in order to contrive subsequent minute contamination, the use of hydrogen for machine insulation, and of sodium for conductors, the projects to which I have referred do not seem so fanciful.

I should like to refer to an experiment which, because it is rather bizarre, I have reserved for the end of my lecture. In a quartz tube there is a glass rod which has been previously heated, and a voltage is applied between its two ends. As the temperature rises and the resistance of the glass falls, current begins to flow, and eventually the glass is maintained at incandescence solely by

the current passing through it. Here is one of the oldest insulations in the world behaving very well as a conductor. It is a sort of incandescent lamp with a glass filament.

CONCLUSION

In conclusion, I should like to encourage insulation engineers to "get busy," if not on my suggested lines, on others they may judge more promising. I should like, for example, to see them show the organic chemists what more can be done with inorganic media, which have temperature and fire resistances of an order that has never yet been associated in practice with impervious, continuous and flexible films.

ACKNOWLEDGMENTS

I wish gratefully to acknowledge the help that has been accorded me, in collecting the data and setting up the experiments for this lecture, by several of the members of the staff of the research laboratory which I have the honour to direct.

DEVELOPMENTS IN SURGE RECORDING BY MEANS OF THE KLYDONOGRAPH*

By J. L. CANDLER, B.Sc.(Eng.), Associate Member.

(Paper first received 1st February, and in revised form 2nd March, 1940; read before the METER AND INSTRUMENT SECTION 5th April, 1940.)

SUMMARY

During the past six years an investigation has been in progress to determine, by means of continuously-recording klydonographs, certain features of voltage surges (and primarily those due to lightning) on overhead lines. This account is based on E.R.A. Report Ref. S/T26, and is mainly concerned with the instruments and their auxiliaries.

The subject matter is divided into six Sections. Section (1) is a brief and general account of the investigation, and mentions the factors necessitating improvements to the apparatus employed.

Section (2) describes the improved klydonographs and gives an account of some of the defects overcome. The phenomenon of cyclic intermittent film motion is considered in detail.

Section (3) deals with the potential-dividers, and the auxiliary equipment thereof, used in this investigation. Specific reference is made to the development of unit-type dividers.

Section (4) deals with calibrations, and indicates the limitations of 50-cycle calibrations used for the estimation of impulse voltages. Calibrations performed at the Association's laboratory are described, and the voltage limits and probable accuracy of recording are stated.

Section (5) concerns the investigations in the field. A brief description of the tests is followed by an analysis of the results obtained.

Section (6) draws conclusions from the six years' work. Although only few records of surges due to lightning were obtained, both the apparatus and technique employed have been considerably improved, and valuable experience has been acquired. From this, conclusions and recommendations pertinent to the klydonographs and auxiliary apparatus are stated. The sparsity of lightning surge records, common with this type of investigation, permits only few and tentative conclusions to be drawn regarding the nature of lightning disturbances on overhead lines. Switching surges are mentioned briefly.

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* Official communication (Report Ref. S/T27) from the British Electrical and Allied Industries Research Association.

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- (7) Acknowledgments.

(1) INTRODUCTION

In 1933 a considerable amount of investigation had already taken place, chiefly in foreign countries, with a view to determining, by means of klydonographs, the effects of lightning discharges upon overhead lines. The advent of the National Grid stimulated the interest in the subject in this country. Whilst it was realized that the published information could be usefully applied, it was also realized that, as the results were dependent on so many variables, this should be done with great discretion, and a similar but independent investigation could with advantage be undertaken in Great Britain.

This was undertaken by the British Electrical and Allied Industries Research Association, with the co-operation of the Central Electricity Board and the Yorkshire Electric Power Co. The complete investigation included the use of a high-voltage cathode-ray oscillograph and magnetic links in addition to continuously-recording

klydonographs; only the last-mentioned are considered in this report. It was agreed that these instruments could not be regarded as accurate peak surge voltmeters, but that they should be capable of indicating the approximate magnitudes, polarities, and times of occurrence of voltage surges. These considerations, together with their relative cheapness in cost and operation, justified the use of klydonographs rather than cathode-ray oscillographs at a number of sites where lightning voltage surges might be expected.

The investigation commenced in 1933, on an 11-kV line owned by the Yorkshire Electric Power Co. Three continuously-recording klydonographs were coupled to the line by means of concentric-cylinder type capacitance potential-dividers. It immediately became apparent that considerable improvement to both klydonographs and potential-dividers would be essential if reliable records were to be obtained. The klydonographs were mechanically unsound for unattended use, and new ones, embodying more powerful motors and other improvements, were obtained. The potential-dividers were found to possess insufficient capacitance between line and tapping, with the result that stray and variable capacitance between tapping and earth affected the voltage ratio excessively. A condenser-bushing type divider, with a higher capacitance between line and tapping, was therefore substituted. Later, high-voltage capacitor units for unit-type dividers were developed.

Recording with the new equipment commenced in 1934, and, whilst better results were obtained, the instruments still needed both mechanical and electrical improvement. They were accordingly subjected to tests extending over a considerable period, and various modifications were made. Progressive elimination of defects resulted in reliable and satisfactory operation by May, 1937, since when no noteworthy trouble has been experienced.

In that year, however, it was found that the 50-cycle voltage ratio of the unit-type potential-dividers was intermittently liable to considerable reduction, resulting in the appearance of spurious 50-cycle figures in the records. The trouble was traced to the porcelain surfaces of the capacitor units (which were in this instance connected to the Rotherham-Doncaster line of the Central Electricity Board) becoming polluted and wet. A series of laboratory tests resulted in a solution to this trouble; an account of these tests appears in Section (3).

During the investigation, which took place on 11-kV and 33-kV lines in various parts of the country, 15 surges were recorded during thunderstorms, in addition to a large number of minor surges considered to be due to switching operations. Both the number and magnitude of the former are disappointing, but the performance of the instruments and their auxiliaries is now considered to be entirely satisfactory.

(2) KLYDONOGRAPHS

(a) General

This Section consists mainly of a description of the improved instruments. Some of the points raised are in themselves only trivial, but have been included because they did, in fact, affect the records.

(b) Principle of Operation

The principle of operation of the klydonograph is essentially very simple. It will be recalled that with an electrode and film arrangement as shown in Fig. 1, the momentary application of a high voltage across the electrodes will produce a distinctive figure on the film after development. This figure is known as a photographic Lichtenburg figure, or klydonogram, and from its size and type certain features of the voltage causing it can be deduced. By causing the film to slide between the electrodes at a known rate, the time of occurrence of the surge can be estimated.

Generally two films and two pairs of electrodes are used. One of these pairs has the hemispherically-ended electrode connected to the potential-divider, and the plate electrode connected to earth; this is known as the "normal" pair, and figures produced by it are called "normal" figures. The other pair has the above connections exchanged and is called the "reverse" pair, producing "reverse" figures. This double arrangement is

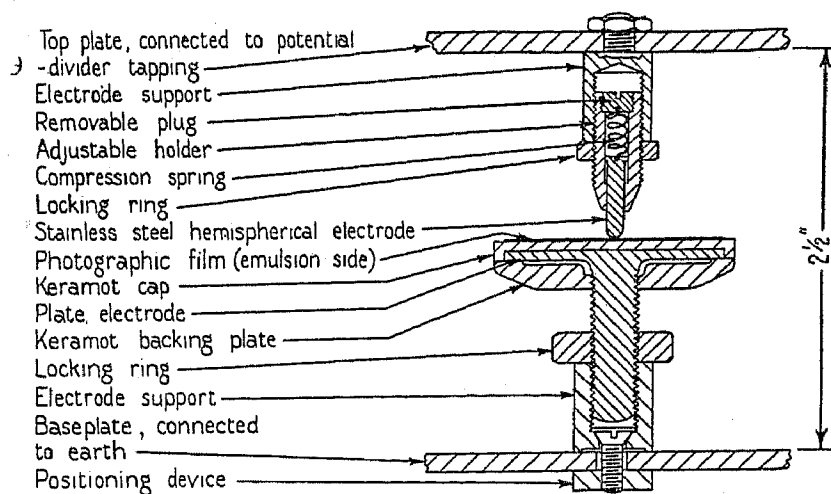


Fig. 1.—Sectional view of normal electrode pair.

employed because the negative figure, produced if the rounded electrode be given a negative potential with respect to the plate electrode, is much smaller and yields less information than the positive figure produced by the application of a corresponding positive potential. The use of two pairs of electrodes ensures that a positive figure will be produced irrespective of the polarity of the applied impulse. Moreover, by comparing the two concurrent figures no doubt exists regarding the polarity of the voltage producing them.

(c) Description of Klydonographs

The complete instrument consists essentially of three parts; (1) a light-proof box, containing the spools of unused film, the electrode system, and the feed-control sprocket wheels, (2) a smaller light-proof box, called the take-up box, containing spools on to which the used film is wound, and (3) a compartment containing two clock-work motors, one being controlled by an escapement mechanism and connected to the sprocket shaft, and the other having no escapement and being connected to the spools in the take-up box.

Hundred-foot reels of 35-mm. film are used, and the

travel rate is 1 in. per hour. Thus the films last for about 7 weeks, but provision is made for cutting off the used film when desired, and two interchangeable take-up boxes are therefore provided for each instrument. Normally, cutting off is performed at about fortnightly intervals, but it may be performed immediately in the event of a line disturbance.

Each instrument is equipped with a mechanical device

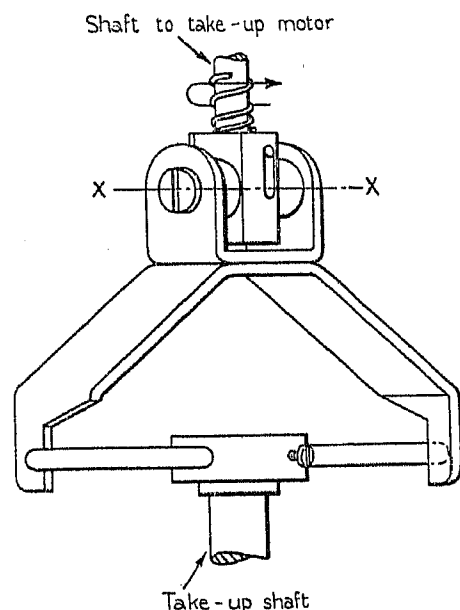


Fig. 5.—Pin and hinged-fork take-up coupling, fitted on modified instruments. Driving radius 2 in.

for applying timing marks to the record at will; time-marking is performed at least once a week.

(d) Improvements Effectuated

The instruments first used, in 1933, were not suitable for use unattended. The new instruments were more satisfactory, but still required improvement. Their poor operation was mainly due to mechanical defects, but it

the film, and the phenomenon is referred to in this report as "snatching." It is considered in detail in Section (2)(e).

Many of the other troubles were due to shrinkage of the wooden cases, which received general attention and treatment with waterproof paint. No trouble from light-penetration through splits has since been experienced, but it is still necessary to allow for deformation.

The following is a list of the more important of the remaining improvements effected:—

(1) The lower electrodes were originally supported on a baseplate, and the upper electrodes on the underside of the lid. This arrangement was found unsatisfactory, as the electrodes became displaced with respect to each other and the centre of the film width. The entire assembly is now located from the baseplate.

(2) Fogging of the film occurred at the junction between the take-up box and the recording compartment. This was prevented by gluing a felt frame to one of the junction faces, and holding the other junction face in contact with it by means of strong springs, visible in Fig. 2.

(3) Silica-gel desiccators are used for drying the air inside the recording compartment. Experience shows that these should communicate freely with the air to be dried, and should be changed at least once per week. They are now mounted actually inside the recording compartment, with a light trap so arranged that they may be changed at will without causing fogging.

(4) Loose gel may cause dark spots or lines on the film after development. The light trap was therefore made to form also a tray under the gel; this is visible in Fig. 3.

(5) The hemispherical electrodes were originally made of brass. It was found that the surfaces of these became roughened during use, and tests with various materials have shown that stainless steel ones are preferable.

(6) Attention was directed towards improving the retractable couplings connecting the timing motor to the sprocket shaft, and the take-up motor to the take-up shaft. The original provision for misalignment proved

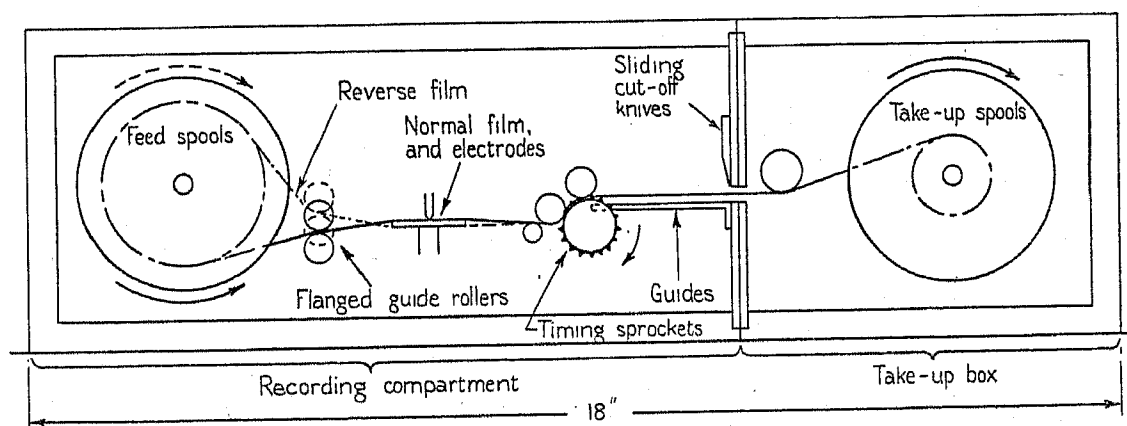


Fig. 6.—Line diagram of modified klydonograph.

was found possible not only to overcome these but also to improve the electrical characteristics. Figs. 2 and 3 (Plate 1, facing page 604) show the klydonographs in their present form.

Apart from stoppage of the mechanism, one persistent trouble was the breakage of the normal-voltage line into a chain of short lines and short gaps, as shown in Fig. 4 (Plate 2). This effect is produced by irregular motion of

inadequate, and the timing coupling was replaced by a single-ended pin-fork coupling. The type of take-up coupling finally employed was as shown in Fig. 5, and by virtue of the double-ended hinged fork this transmits an almost pure torque even if considerable misalignment be present.

(7) The passage of the film over the sprocket wheels received attention, as trouble had been experienced due

to the film riding off the sprockets, slipping over them, or becoming wrapped around them. Firstly, rollers grooved to clear the sprocket teeth were arranged so that the film lapped round the sprockets sufficiently to ensure that at least one tooth projected through each line of perforations at any one instant, as shown in Fig. 6. Secondly, a guide was provided on the pull-off side to slide the films off the sprockets in the event of any tendency to stick. Finally, the tooth-profile was modified as follows:—

It will be realized that, relative to the rotating sprocket wheels, the path of any point on the film approaching the sprockets and near to them is epicycloidal in form, and similarly when just leaving the sprockets is of involute form. These curves, drawn in the correct direction from the base of the sprocket profile, cross and form an inverted V-shaped figure. The profiles were made to lie clear of the above curves, to permit each tooth to enter or withdraw from a perforation without touching the film except when it is lying on the cylindrical portion of the sprocket wheels.

(8) It will be noticed in Fig. 6 that it has been arranged for the films to bend slightly at the front and back edges of the plate electrodes. These bends were introduced to encourage the films to lie flat on the plate electrodes.

(9) To reduce friction, rollers were provided at suitable points, and the ratio (effective diameter/bearing diameter) was made as large as possible. In addition, the flanges of the take-up spools were spun out to a slightly conical shape to prevent the film scraping on them.

(10) The sulphide bronze finish on certain of the metal parts was found to interfere with their correct operation; from these it was removed.

(11) It was found necessary to make provision, on certain of the rollers, for variations in the width of nominally 35-mm. film.

(12) Experiments showed that the celluloid film became charged when drawn over the bakelite plate-electrode caps originally fitted, and tended to "wring" on to them. Considerable improvement resulted from painting a solution of the film on to the caps so as to leave a thin layer of celluloid adhering to them. Subsequently, however, it was found that Keramot caps could be employed without this celluloid layer, as reported in Section (2)(h)(ii).

These improvements considerably reduced the amount of trouble experienced. Further improvement resulted from the substitution, at a later date, of the new electrodes with Keramot caps.

(e) Investigation of Snatching

When a klydonograph is operating correctly, the forward motion of the films is produced entirely by the take-up motor, the timing motor permitting the films to move only very slowly. This fact leads to an explanation of the phenomenon of intermittent motion of the film without stoppage of the timing clock, as follows:—

(1) Excessive stiffness causes the take-up motor and film motion to stop. This does not, however, cause the timing motor to stop.

(2) The slackness in the coupling between the timing motor and sprocket shaft is slowly taken up, after which the sprocket wheels slowly rotate, and their teeth

from the back edges to the front edges of the film perforations.

(3) Further movement of the sprocket wheels causes the film to move forward; this usually allows the take-up motor to restart. If it does, uniform motion may ensue, but generally the conditions are such that the take-up motor pulls the film faster than the normal speed of 1 in. per hour permitted by the timing motor, and the speed is usually sufficient to prevent the formation of the normal-voltage line. This rapid motion continues until the sprocket teeth are again in contact with the back edges of the film perforations and slackness in the timing coupling has been taken up. The motion may now become uniform, but in many cases the above cycle of events is repeated, giving a record of the type shown in Fig. 4(a).

By making the take-up motor sufficiently strong, snatching can be prevented. Tests indicated, however, that it was already strong enough under normal conditions, and attention was therefore directed towards determining the obscure reasons for this phenomenon and for complete stoppage. They were as follows:—

(1) Excessive and variable friction at numerous points; reduced as under Section (2)(d).

(2) Excessive static friction in the take-up motor; reduced by removing the overspeed governor and the gear train driving it.

(3) Film "wringing" on to the bakelite caps; almost prevented as described in Section (2)(d).

Laboratory records before and after the above alterations are shown in Figs. 4(b) and 4(c).

A further cause of snatching and stoppage was discovered in 1937; this is considered in Section (2)(h)(ii).

(f) Laboratory Field Hut

It is essential that in making tests on klydonographs the conditions should simulate practical conditions as nearly as possible. For this reason a test hut was erected in the field behind the laboratory building, and a potential-divider mounted above it. In this hut the instruments are under normal atmospheric conditions and are relatively free from vibration, which generally improves their operation. The requisite voltage is supplied by a transformer, either directly or through the potential-divider.

Entering the hut was found in some cases to affect the operation of the instruments under test. Arrangements were therefore made for checking their operation from outside the hut, by means of two devices as follows:—

(1) A brass sounding-rod was connected to the motor compartment. This rod passed through the hut wall, and terminated outside in a small ebonite knob. By placing the knob in the ear it was possible to determine whether the timing motor was running.

(2) A special coupling fork was fitted to the sprocket shaft. This was identical with the normal fork except that one of each pair of prongs was made narrower to accommodate a piece of bicycle valve rubber stretched over it. A low-voltage circuit was arranged to include the pin and fork of the coupling, so that only under normal conditions, with the timing motor restraining the sprocket shaft, was the circuit complete. A lamp outside the hut was included in the circuit to give visual indication of the

(g) Routine Tests

Before being passed for service the instruments are given the following tests:—

- (1) A run-down test.
- (2) A travel-rate test.
- (3) A 50-cycle breakdown test.
- (4) An impulse-voltage test.
- (5) An insulation-resistance test.

The run-down test is carried out in the field hut. The instrument is started off with normal voltage applied, and it is then allowed to run, without assistance, until it stops. The period run should be at least 10 days.

The actual travel-rate is similarly checked under practical conditions.

The 50-cycle breakdown test consists of applying a slowly-rising alternating voltage between the high-voltage terminal and the earth terminal until internal flashover occurs. This voltage was not less than 10 kV (r.m.s.) for the $\frac{7}{8}$ in. diameter electrodes, and not less than 11 kV (r.m.s.) for $1\frac{3}{8}$ in. diameter electrodes, now standard.

The impulse-voltage test consists of applying, as above, 10 positive and 10 negative 17-kV impulses with a steep front and a 50-microsecond tail to half value, whilst watching for breakdown with a cathode-ray oscillograph.

The insulation-resistance test is made with a high-range insulation tester both before and after the above voltage tests. The value between live and earth terminals is about 1 000 megohms, and should be sensibly the same before and after.

(h) Miscellaneous**(i) Hairy broadening of the normal-voltage line.**

It is interesting to note that the hairy broadening of the normal-voltage line sometimes obtained in practice was reproduced, as in Fig. 4(c), in the laboratory field hut, in which the instruments are fed directly from a transformer. This is of some importance, as it has been stated by some investigators that this broadening could be caused by transient over-voltages due to surface discharge over polluted line insulators, as under very humid conditions. Whilst this may be so, the broadening must not be taken as definite indication of surface discharges and their associated over-voltages, as it can be produced by raising the 50-cycle voltage slightly above the minimum required to form a normal-voltage line. Moreover, with certain types of potential-divider, pollution and dampness can produce an increase in the 50-cycle voltage applied to the instrument.

(ii) Phenomenon of film seizure.

In connection with the tests on the pollution of potential-dividers, reported in Section (3), it was found that the 50-cycle tapping voltage could, under extreme conditions, rise considerably above the value which produced hairy broadening. One effect of this greatly increased voltage was to produce large and dense figures, elongated by the motion of the film into a wide strip. Another effect was greatly to increase the pull required to draw the film between the electrodes. In some cases

stoppage occurred, and the elongation mentioned did not take place. Tests showed that the subsequent fall towards normal of the 50-cycle voltage generally permitted the instruments to restart. Thus some figures appeared in the records which were very similar to those produced by Petersen coil operation, and it was at first thought that this was their cause. Fig. 7 illustrates the above notes.

The exact nature of this phenomenon is not known, but it has been verified that the pull necessary to cause continuous motion during over-voltage is considerably less with the new type of electrodes fitted with Keramot caps, and that the instruments continue to operate satisfactorily up to a 50-cycle voltage of at least 6.6 kV (r.m.s.)—a value never reached in practice.

It is clear from the foregoing that an intermediate rise in voltage from the above causes could have, and doubtless has, produced snatching in an instrument fitted with the original type of electrodes and which is, in itself, perfectly sound.

(iii) Present standard of recording.

Experience since 1937 indicates that both electrically and mechanically the Association's klydonographs are now satisfactory. Their mechanical reliability has reached a very high standard, and their electrical performance, dealt with more fully in Section (4), could not be appreciably improved with this type of instrument.

(3) POTENTIAL-DIVIDERS**(a) Choice of Voltage-ratio**

The useful voltage range of the klydonographs used by the Association is approximately from 3 to 15 kV (peak); for this reason it is necessary to couple the instrument to the line through the medium of a potential-divider. In all cases a capacitance potential-divider has been used, and the voltage ratio has been so adjusted that the normal voltage of the line to earth applied to the divider gives a tapping voltage which produces a small circular mark at the electrodes, elongated into a fine line by the motion of the film. This voltage is dependent to a certain extent on the size of the electrodes, size and material of the insulating cap, and also upon atmospheric conditions, but may be taken as 1 700 volts (r.m.s.) for the electrodes now standard and under normal conditions. The reasons for this choice of voltage are as follows:—

(1) The instrument, set up in the above manner, is capable of satisfactorily recording surges with peak values between approximately 1.2 and 6 times normal voltage—i.e. times the normal peak voltage to earth. It is within this range that most surges hitherto recorded fall.

(2) By running so as to produce a thin line by means of the 50-cycle voltage it is possible to say whether the line was energized at any particular time.

(3) The normal-voltage line acts as an indicator of the behaviour of the instrument, as indicated in Figs. 4(b) and 4(c).

(b) Types of Capacitance Potential-divider

Various types of capacitance potential-divider are available, of which the Association now uses two for

klydonograph investigations. The salient requirements of an ideal divider for this work are as follows:—

(1) Constancy of voltage ratio under all conditions of voltage, rate of change of voltage, temperature, pollution and wetness.

(2) A capacitance value between line and earth which is high enough to mask the effects of variable stray capacitances, and yet not so high as appreciably to affect the passing surge voltage. It was found by calculation that a capacitance of $100\ \mu\text{F}$ had a negligible effect on both peak voltage and wave-form. It was decided to use this value for 33-kV lines, and it follows that with the unit-type divider the capacitance would be $300\ \mu\text{F}$ for an 11-kV line. Although this latter figure might be high for use with a cathode-ray oscillograph, it would not have an appreciable effect on the accuracy obtainable with a klydonograph. No other line voltages have yet been used.

(3) A breakdown-voltage in excess of that of the insulation of the line to which the divider is connected, under any identical atmospheric conditions.

The two types at present in use are the tapped condenser-bushing type and the unit-capacitor type. The former, used for 33-kV lines, consists of a 44-kV condenser bushing mounted on an oil-filled tank. The upper end of the central conductor is connected to the line, and the lower end terminates, within the oil, in a small sphere. A tapping from one of the metallic layers of the bushing is brought out under oil, and emerges from the tank through a low-voltage bushing. The tank is earthed, and the tapping voltage can be adjusted within wide limits by connecting suitable low-voltage capacitors between the tapping and earth. The performance of this type of divider is extremely good, particularly with regard to constancy of voltage ratio, provided certain precautions are taken. They are, however, rather expensive, heavy, and awkward for raising to a tower cross-arm. In addition, they are not particularly robust.

The unit capacitor type of divider was developed to overcome the above disadvantages, and has the additional advantage that a given stock of units can be built up in different ways to form dividers for various line voltages according to requirements. Under severe conditions of combined pollution and wetness, however, this type has been found to be subject to instability of the 50-cycle voltage ratio. The importance of this should not be over-stressed as, fortunately, the impulse voltage ratio is probably affected to a negligible extent. An investigation of this instability is described later in this section of the report.

In the unit-type potential-divider the high-voltage section consists of one or more identical capacitors, each of $0.0003\ \mu\text{F}$ capacitance and rated at 11 kV, and each contained in a porcelain cylinder fitted with rain sheds. Each porcelain cylinder has metal bolting-flanges and cover-discs at both ends. These seal the capacitor within the cylinder and form the capacitor terminals; thus bolting together successive units to form a pile also connects in series the successive capacitors. This high-voltage section is mounted on an empty porcelain cylinder of the same type for insulation purposes. The divider is completed by connecting low-voltage capacitors between the lowest flange of the high-voltage portion and earth:

the tapping point of the divider is thus the last-mentioned flange.

This type of divider is reliable, robust and relatively cheap and, by virtue of its unit form, readily portable. Its electrical characteristics are very satisfactory, with the one exception considered in the following Section.

(c) Improvements to Unit-type Potential-dividers

During the tests in Yorkshire in 1937, using dividers of the above type, 50-cycle figures appearing intermittently in the records indicated the presence, at the tapping point of the divider, of alternating voltages considerably in excess of normal, and sometimes persisting for periods of up to an hour or more. Actual voltage measurements during a brief shower showed that the tapping voltage did rise considerably. Since there was no evidence of abnormal line voltage at the time, this appeared to be due to a reduction in the 50-cycle voltage ratio, probably caused by combined pollution and wetness of the exposed surface of the potential-divider.

Tests on a typical 11-kV outdoor site erected at the Association's laboratory, using a single-unit divider of the above type, confirmed this, and klydonograph records similar to those obtained in Yorkshire were produced. Prints of service and laboratory records are shown in Fig. 7 (Plate 2) for comparison purposes. It will be noticed that the service record shows a circular figure, not elongated as in the laboratory record. This might indicate that the service over-voltage was only momentary, but in the light of more recent knowledge of the effect of over-voltage on the resistance of the film to motion it is quite possible that during the over-voltage period the clockwork motors were forcibly stopped, and that they restarted when the voltage fell towards normal. The fortnight's record, approximately 28 ft. long, might be only a fraction of an inch shorter on this account, and brief stoppage of this nature is very difficult to detect from the records.

The laboratory tests established the following:—

(1) Pollution of the exposed surface of a unit-type divider, as with coal dust and ash, combined with wetness, can considerably reduce the 50-cycle voltage ratio.

(2) One only of the above conditions does not measurably affect the 50-cycle voltage ratio.

(3) The reduction in ratio is due to a fall in the leakage resistance along each porcelain cylinder.

It is unlikely that these conditions affect to any appreciable extent the voltage ratio under high-frequency a.c. or surge conditions. The surface-leakage path forms a resistance potential-divider connected to the capacitance potential-divider at each flange, and efforts to stabilize the 50-cycle voltage ratio have aimed at insulating the capacitor junctions from the leakage paths. Such insulation should possess high resistance and low capacitance, and of the various methods of insulation tried the best results were obtained with the arrangement shown in Fig. 8. It will be seen that the capacitors are disconnected from the flanges, by substituting insulating cover-discs for the metal ones at both ends of each porcelain cylinder, except in the case of the top unit, which has only its lower end modified. Connection between capacitors is made by small plates at the centre of the discs,

one of each pair being fitted with a spring-loaded plunger. The top of the insulating base is, of course, modified similarly, and the down-lead brought away from within the porcelain cylinder in a sealed connector described later.

An idea of the stability of 50-cycle voltage ratio effected in this way may be obtained from Table 1.

Table 1

	Approximate characteristics of cover-discs		Maximum decrease in 50-cycle ratio
	Capacitance	Insulation resistance	
Normal 11-kV divider ..	$\mu\mu\text{F}$	M Ω	%
Modified 11-kV divider ..	14	0 ∞^*	66 2.2

* This reading was obtained with an insulation tester having highest markings of 2 000 M Ω and infinity. No deflection from the infinity mark could be observed.

In the above tests the voltage ratio with the divider dry and clean was adjusted to 6.2 instead of the normal value of about 4 used in service. This was done in order to increase the effects of combined pollution and wetness.

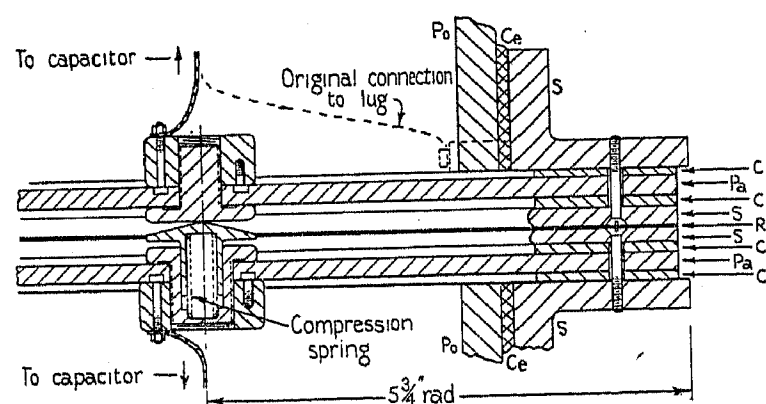


Fig. 8.—Sectional view of connection between modified units of potential-divider.

Ce = cement. C = cork gasket. Pa = Paxolin disc.
P0 = porcelain cylinder. R = rubber gasket. S = steel.

Calculations show that for an 11-kV divider and a ratio of 4 the decrease in ratio would probably not exceed 1 %, and that for a 33-kV divider and a ratio of 12, about 3 %. These figures have been verified by tests and are considered to indicate satisfactory stability.

(d) Voltage-adjusting Capacitors

These are rated at 2 kV (r.m.s.) continuous, and are built to withstand surges of considerably higher values. They are mica-insulated and rated at 0.0001, 0.0002 or 0.0005 μF capacitance.

Little trouble has been experienced with these, although occasionally cases of low internal resistance occur as reported in Section (3)(f). To reduce surface leakage stiff tough-rubber-sheathed cable is used for connection, and each terminal is encased in a bakelite cap, subsequently sealed off with compound. To prevent flexing of the cables within the compound they are clamped to the side of the capacitor case.

It should be noted that when used in conjunction with a unit-type divider these low-voltage capacitors generally form the bulk of the low-voltage section of the divider. In a few cases, however, it has been found that the capacitance of the down-lead is sufficiently great to necessitate little or no added capacitance.

(e) Down-lead

At outdoor sites a cable, with the core at tapping potential, is run down the tower and into the test hut.

At the sites first used this conductor consisted of an ignition flexible cable, tied to the tower leg at intervals and brought up under the eaves of the hut roof to prevent entry of rain. It was found that the tough rubber sheath rapidly deteriorated, and also that the core-to-earth capacitance was liable to considerable increase when the surface of the cable became covered with a moisture film.

Some improvement as regards the latter objection resulted from spacing the cable away from the tower leg with tarred-string pull-offs. The obvious solution involving the use of a screened cable of the normal type was impracticable, since although capacitance variation would be small the actual capacitance value would be excessive.

A special low-capacitance screened cable, shown in Fig. 9 (Plate 2), is now employed. This type of cable has proved so satisfactory that it is used for all outdoor sites, although its construction is such that certain precautions have to be taken during installation, particularly as regards terminations. Reference to Fig. 9 will assist in making the following points clear:—

(1) The core is insufficiently robust to withstand appreciable axial load. It is necessary, therefore, to ensure that such load is taken either on the braided sheath or on the outer Telconax sheath.

(2) The low value of capacitance, which is of the order of only 15 $\mu\mu\text{F}$ per foot, is obtained mainly by the use of an air-spaced dielectric. It is important that these air spaces be sealed off at the ends of the cable to prevent ingress of moisture.

(3) During installation, the braided sheath is earthed. On account of the air spaces mentioned above, heavy earthing clamps around the sheath must be avoided.

(4) Heating softens both the guttapercha fins and the inner Telconax tube separating core and sheath. Care must be taken to prevent these approaching one another when applying heat to the cable, as when making soldered connections.

(5) The earthed sheath must be bared back within the connector sufficiently to prevent flashover between core and sheath on the highest surge voltage to which the cable may be subjected. For test purposes this is taken as 30 kV.

(6) Sharp bending and/or crushing must be avoided.

Fig. 10 shows a typical connector, used in this case to connect the upper end of the down-lead to the modified unit-type potential-dividers.

(f) Testing

It is important that the potential-dividers used should possess electrical strength superior to that of the line insulators.

In addition to the usual 50-cycle tests, comparative impulse-voltage tests are made. In one such typical test, divider units of $0.0003 \mu\text{F}$ capacitance were subjected to impulse waves of both polarities, two wave shapes, and peak voltages 10 % in excess of the corresponding minimum impulse flashover voltages of typical line insulators. In no case did flashover occur across the capacitor system, and there was no indication of damage sustained by the capacitors.

Breakdown of the klydonograph, low-voltage capacitors or tapping lead would not be as serious as that of the potential-divider, but tests are made to verify that breakdown is improbable. Briefly, the 50-cycle breakdown strength is ample in so far as the 50-cycle voltage is limited to some 2 or 3 kV; impulse voltages are the more likely cause of breakdown.

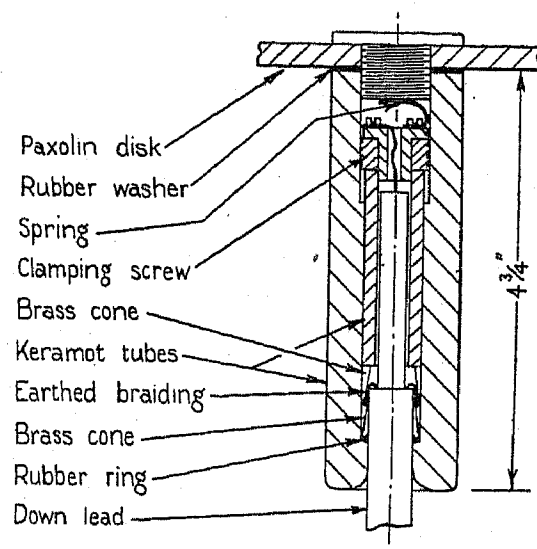


Fig. 10.—Sectional view of upper connector; modified unit-type divider to down-lead.

An impulse which flashes over an 11-kV insulator could apply approximately 50 kV to the tapping system. This voltage (which is beyond the recording range) might cause puncture in the down-lead or the low-voltage capacitors. An upper limit to the tapping voltage is, however, set by the klydonograph, which breaks down, by flashover, on 1/50-microsecond waves at about 18 kV without damaging the instrument. It is safe to assume that this limiting effect applies to the entire length of the down-lead, as this is insufficiently long to permit appreciable voltage variation along its length with any surge likely to be applied to the divider by the overhead line. It is necessary, therefore, merely to test the apparatus in parallel with the klydonograph at a voltage rather higher than 18 kV.

Actually, the down-lead and connectors are tested with alternating voltages of not less than 11 kV (r.m.s.), and with 1/50-microsecond 30-kV waves of both polarities, whilst watching for breakdown with a cathode-ray oscillograph.

Only indirect tests have been made on the low-voltage capacitors, but these appear to withstand all normal alternating and impulse voltages satisfactorily. A few isolated cases of very low internal resistance have occurred, but it has been found that these were more probably due to penetration of moisture into the capacitor than to failure of the dielectric.

(g) Effect of Reflection Resistor

During the calibrations reported in Section (4), using a circuit as shown in Fig. 15, the effect of a resistor R_1 , connected between the lower end of the down-lead and the earthing switch, was examined.

The impulse voltage applied to the potential-divider was a smooth exponential wave. Records were taken of the resulting tapping voltage and are reproduced in Fig. 11 (Plate 3).

Fig. 11(a) shows the tapping voltage obtained with the above conditions but with R_1 removed; the effect of multiple reflections along the down-lead can be clearly seen.

Fig. 11(b) shows the tapping voltage obtained with the above conditions but with R_1 in circuit. This resistor is non-inductive and has a resistance value approximating to the surge impedance of the down-lead, and it will be seen that the steps in the tapping-voltage wave have been removed.

In practice, however, a resistor such as R_1 is not used for the following reasons:—

(1) The effect on the peak tapping voltage of smoothing the wave as above is small for the short wave-front shown. The corresponding effect with the longer wave-fronts which are probable in practice would be less. Provided, therefore, the instruments are calibrated under conditions obtaining in practice, it is of little importance, bearing in mind the voltage accuracy to be expected, whether R_1 be included or omitted.

(2) There is reason to believe that the voltage steps obtained when a resistor is not used tend to produce a clearer klydonogram than that produced with a smooth wave as in Fig. 11(b).

(4) CALIBRATIONS

(a) Calibration of Potential-divider

Tests were made in 1933 on the concentric-cylinder type divider, using 50-cycle voltages. It was found that a slight reduction in voltage ratio (defined as the quotient of the voltage applied to the divider and the voltage appearing across the klydonograph electrodes) resulted when the applied voltage was raised from about 35 kV to 80 kV. There is little doubt that the change in ratio was due to an increase in the capacitance of the higher-voltage section caused by corona, and it has not been considered necessary to repeat these tests on the improved types of divider now in use.

In practice the voltage ratio is taken, for the purpose of estimating voltages from recorded figures, as the 50-cycle ratio measured when the potential-divider and auxiliary apparatus are clean and dry.

(b) Calibration of Klydonograph

(i) Calibration with 50-cycle voltages.

It is well known that calibration curves, connecting figure size and peak applied voltage, for a given pair of electrodes, are similar for 50-cycle figures and positive figures produced by impulse waves. It has even been suggested that a calibration using 50-cycle voltages may be taken to apply to positive figures produced by impulse voltages, and that on account of its greater simplicity this method is preferable.

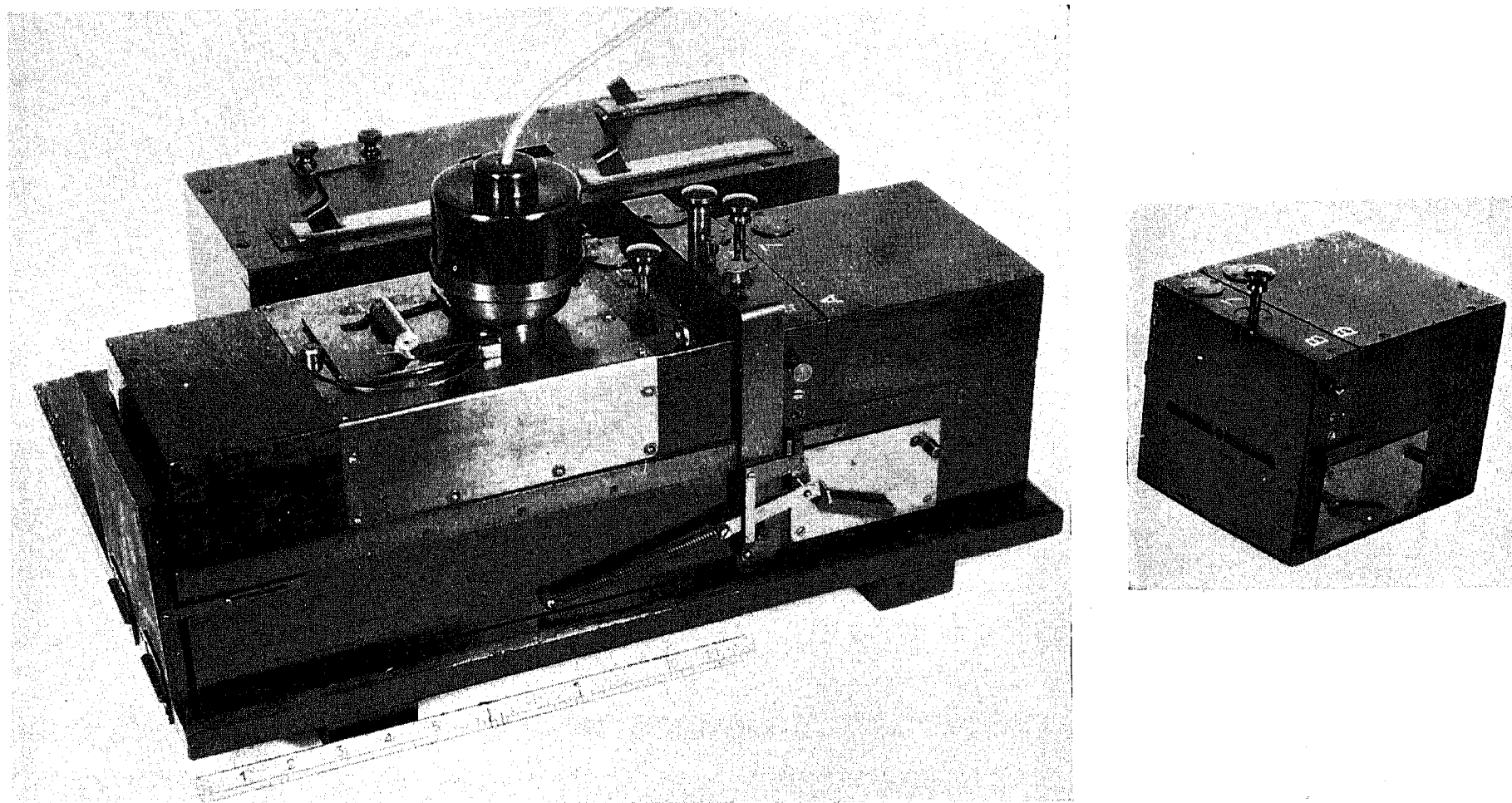


Fig. 2.—Klydonograph and spare take-up box, after modification.

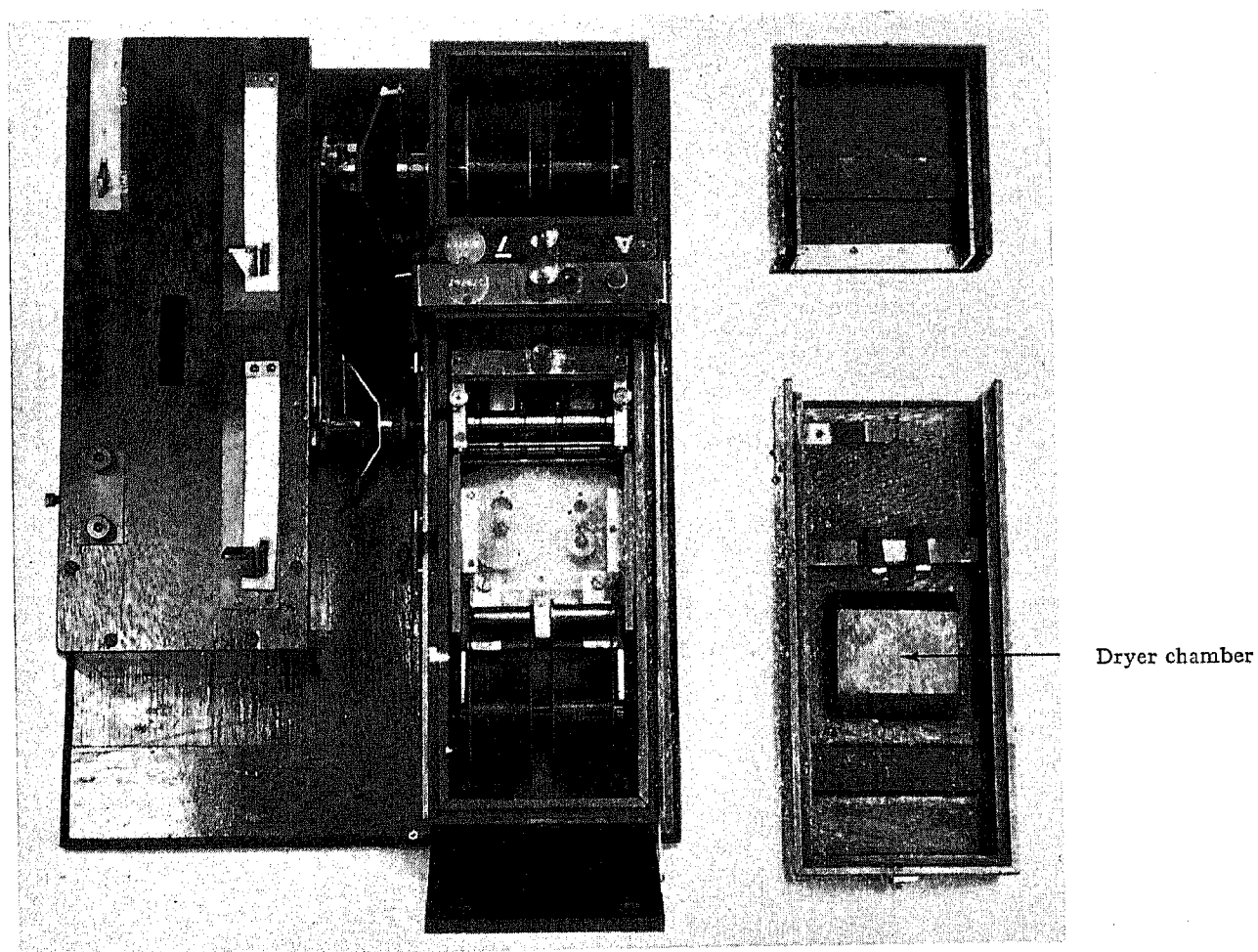


Fig. 3.—View of interior of klydonograph, after modification.

NOTE.—The top electrode plate, apparently transparent, was removed during exposure to show the lower electrodes.

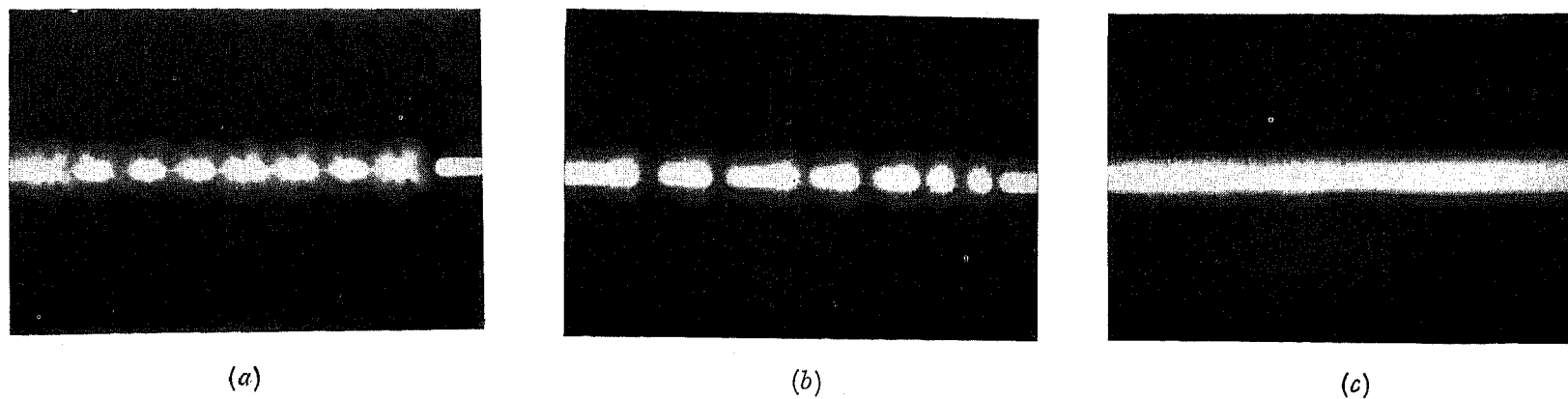


Fig. 4.—Effect of irregular film motion on the normal-voltage line.

- (a) Service record, obtained during 1935; broken line is due to irregular film motion.
- (b) A similar record obtained for check purposes in the laboratory.
- (c) A laboratory record demonstrating the above trouble overcome.

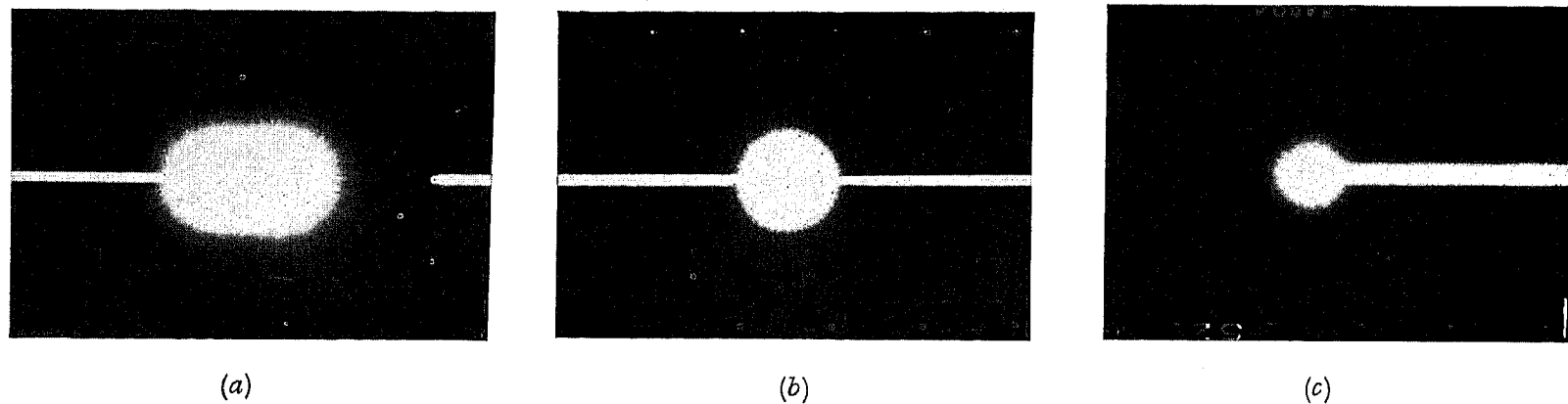


Fig. 7.—Records of 50-cycle overvoltages.

- (a) Laboratory record; overvoltage produced by artificial pollution and wetness of unit-type potential-divider.
- (b) Service record, probably produced by natural pollution and wetness of a similar divider.
- (c) Service record, produced by operation of a Petersen coil.

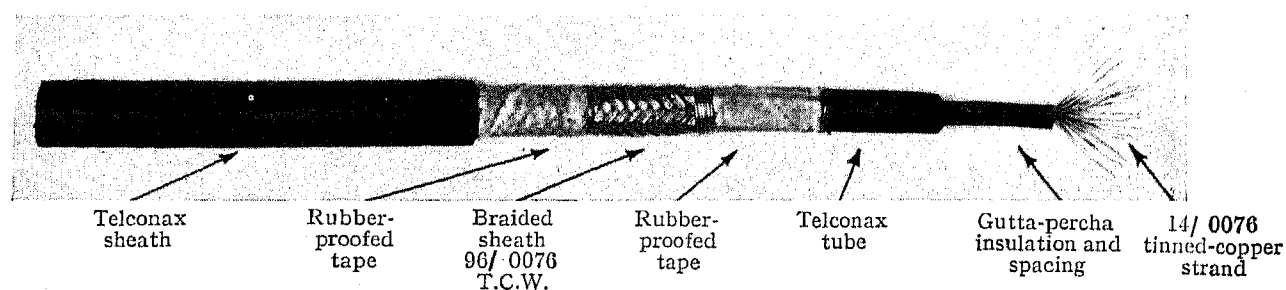
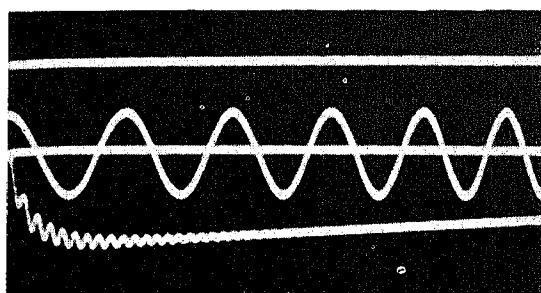
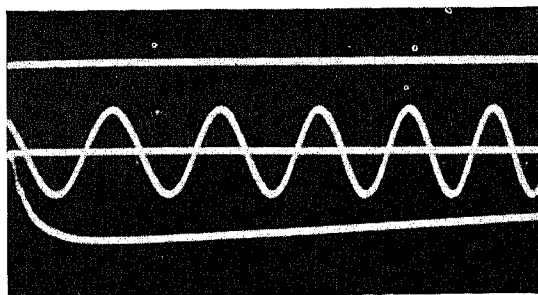


Fig. 9.—Low-capacitance screened down-lead.



(a)



(b)

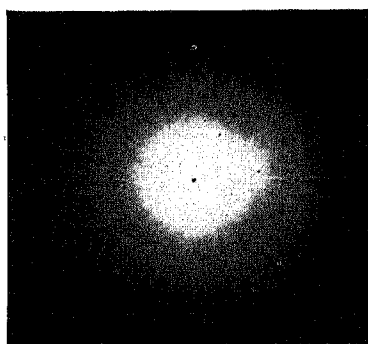
Fig. 11.—Oscillograms of tapping-voltage waves in test hut, showing the effect of a reflection resistor.
Period of timing oscillation, 5 micro-seconds.

(a) Without resistor.

(b) With resistor.



(a)



(b)

Fig. 14.—Typical 50-cycle klydonograms. Duration 0.5 sec.

(a) 6 kV (r.m.s.).

(b) 12 kV (r.m.s.).

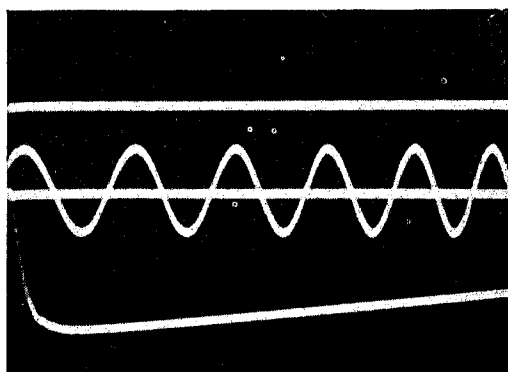
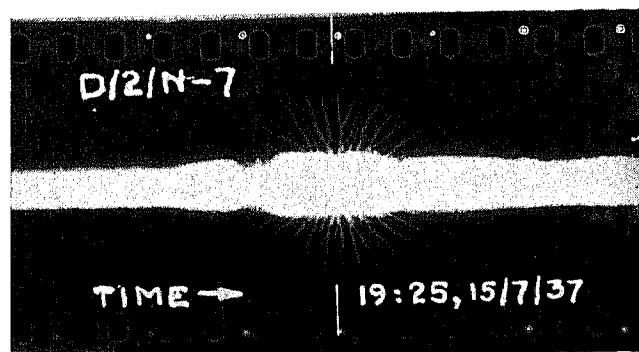
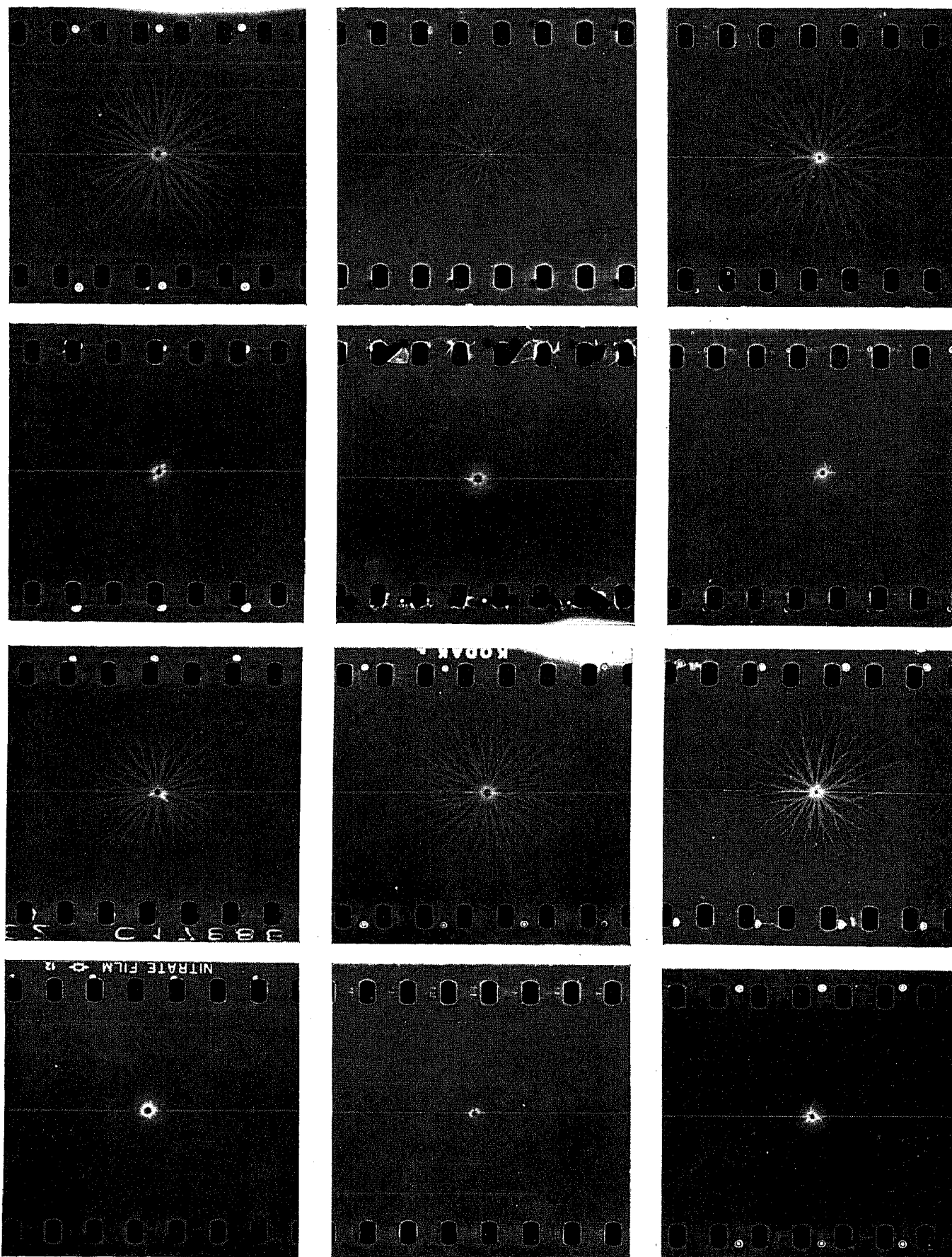


Fig. 16.—Oscillogram of typical 1/50-microsec. impulse used for calibration. Period of timing oscillation 5 microsec.



Normal
record

Fig. 22.—Record of a positive surge on the Rotherham-Doncaster line, obtained during a thunder-storm.



Positive figures.
Positive waves.
Normal film.

Negative figures.
Positive waves.
Reverse film.

Positive figures.
Negative waves.
Reverse film.

Negative figures.
Negative waves.
Normal film.

Plate $\frac{7}{8}$ in. dia.
Hemisphere $\frac{1}{8}$ in. dia.
(Arrangement 1.)

Plate $\frac{7}{8}$ in. dia. (coated).
Hemisphere $\frac{1}{8}$ in. dia.
(Arrangement 2.)

Plate $1\frac{3}{8}$ in. dia.
Hemisphere $\frac{3}{8}$ in. dia.
(Arrangement 3.)

Fig. 17.—Typical klydonograms produced by 5-kV, 1/50-microsec. impulses.

MEANS OF THE KLYDONOGRAPH

Plate 4

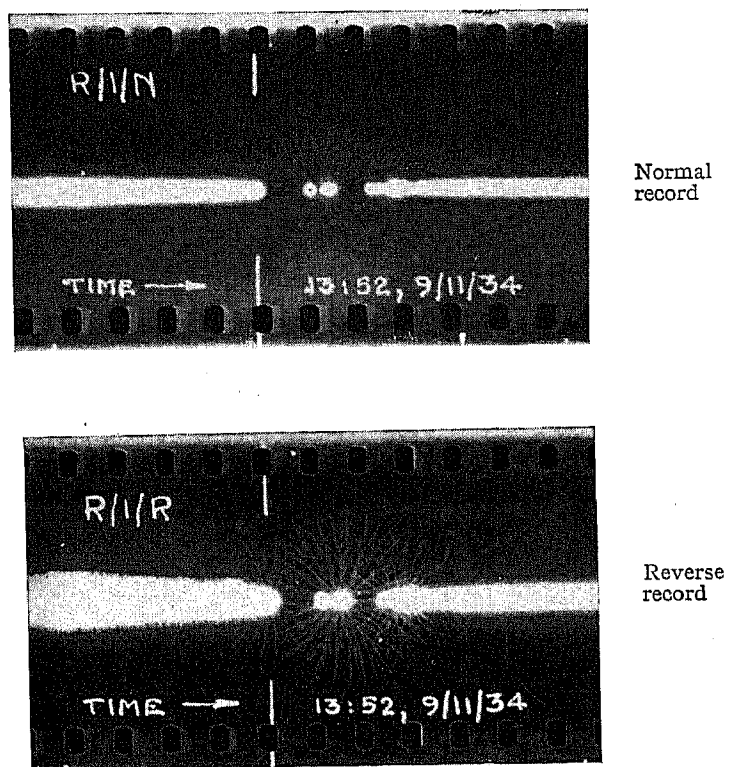


Fig. 19.—Records of switching surges on the Rayleigh-Southend line.

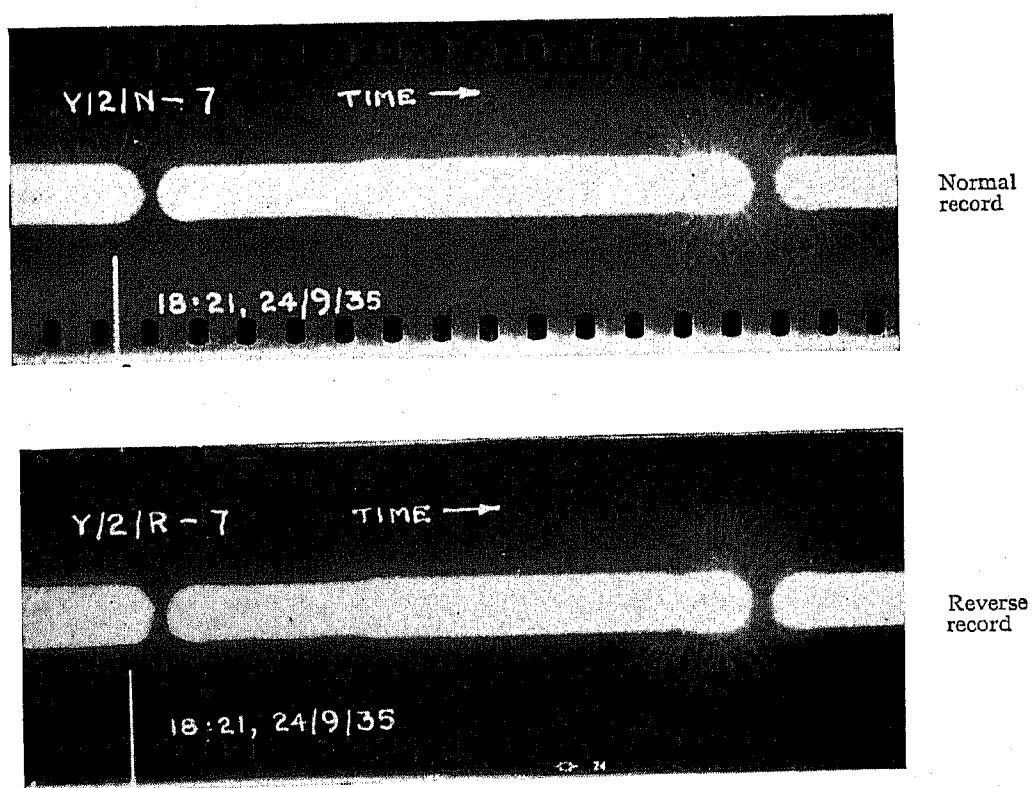


Fig. 20.—Records of surges on the Thornhill-Barugh line, obtained during a thunderstorm.

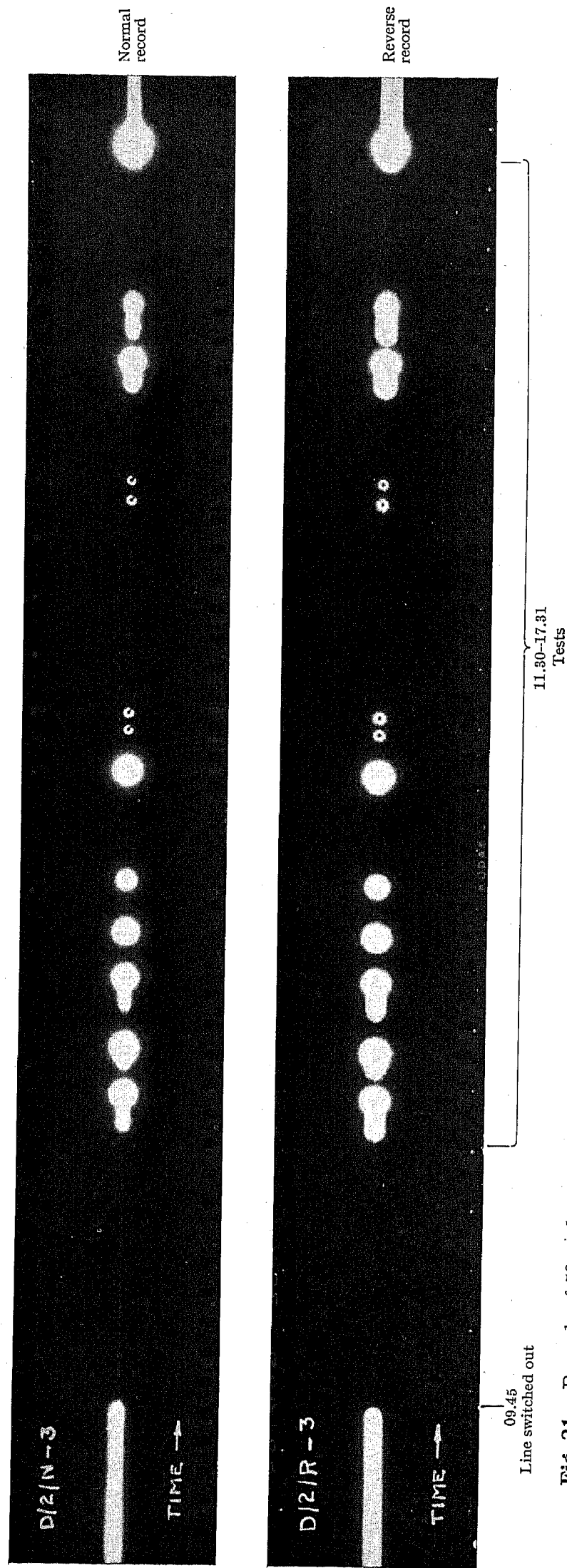


Fig. 21.—Records of 50-cycle overvoltages on the Rotherham-Doncaster line, obtained during commissioning tests on Petersen coils, 9th May, 1937.

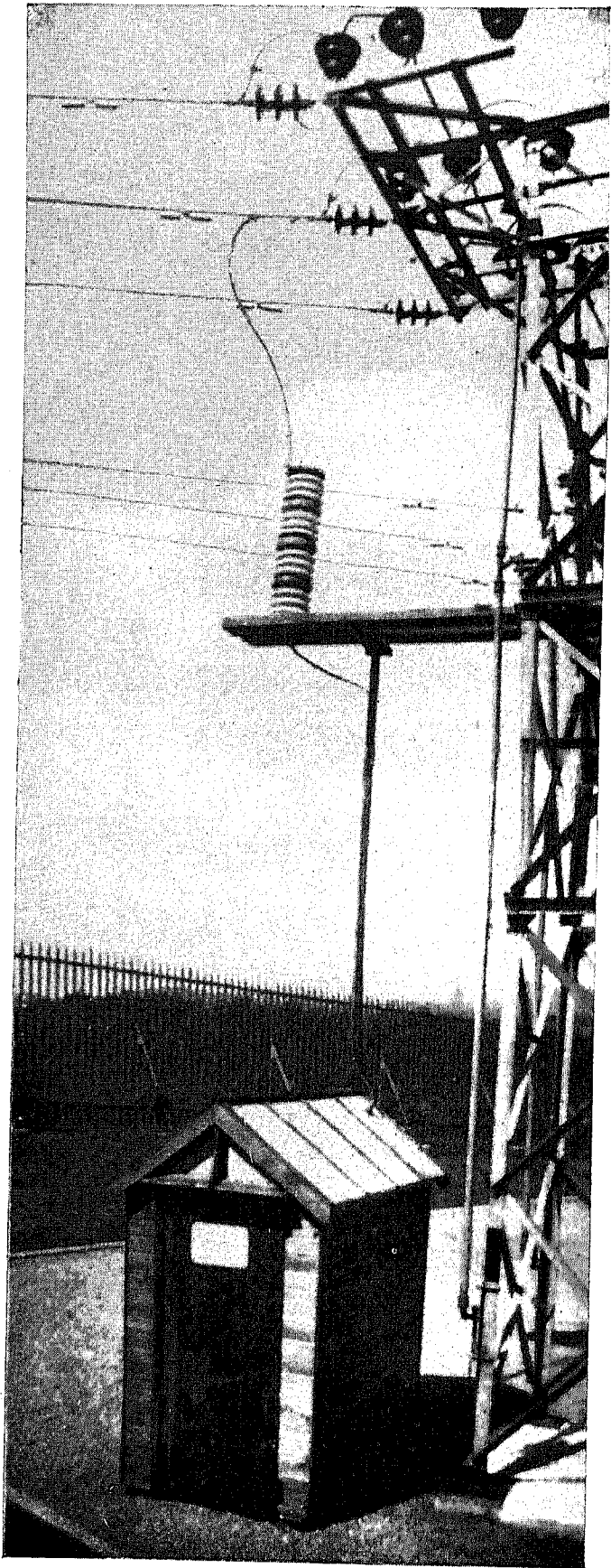


Fig. 23.—Composite photograph of a recording site in South Scotland, showing the test hut, 33-kV unit-type potential-divider, and connections thereto.

It has been found, however, that for a given peak voltage the positive figure produced by an impulse wave is larger than the figure produced by a 50-cycle wave, and it would appear that the 50-cycle calibration is superfluous. Whilst this is partly true, such calibration may be used, for example, to predict approximately the impulse characteristics of experimental electrodes.

The 50-cycle calibration was obtained by applying a range of steady 50-cycle voltages to (1) an instrument fitted with the original type of electrodes, and (2) an instrument fitted with the electrodes now standard. These types are specified in cols. 1 and 3, respectively, in Table 2.

Prior to making these tests, the effect of the duration of application of voltage upon the resulting klydonogram was investigated. Over the range employed it was found that an increase in duration produced a denser figure without appreciably affecting its size.

The circuit was arranged as shown in Fig. 12. Voltages up to 17 kV (peak) were applied. Switch S_2 was specially designed to give rapid closing with little contact-bounce,

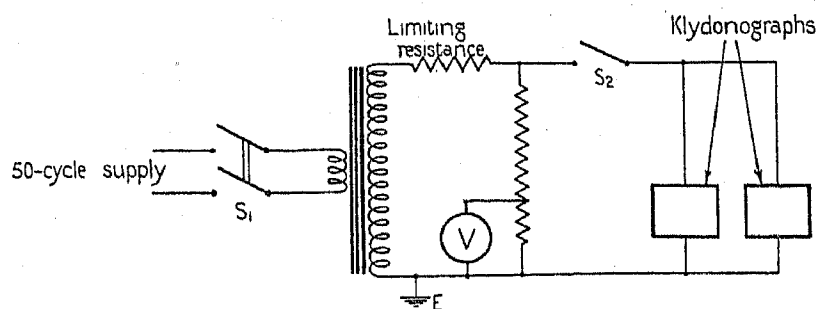


Fig. 12.—Circuit employed for 50-cycle calibration.

and the value of the limiting resistance in the transformer output was such that no appreciable voltage change occurred on closing this switch. All leads were made as short as possible.

Ambient air conditions were noted, but no attempt was made to control them. A silica-gel desiccator was, however, employed to bring the humidity of the air within the instruments to a low value.

Film as used for recording was employed, this being Kodak orthochromatic motion picture negative film, 35 mm. wide.

Results Obtained.

The results obtained are shown graphically in Fig. 13, together with two typical klydonograms in Fig. 14 (Plate 3). For the upper portions of the curves it appears that the plate electrode size affects the figure size, the maximum figure diameter obtainable probably being rather more than the cap diameter. It will be recollected that the instruments flash over at about 16 to 17 kV (peak); the larger electrodes thus permit full use of the film width up to this voltage, and by increasing the diameter/voltage slope tend to increase the voltage accuracy.

(ii) Calibration with impulse voltages.

General.

The first instruments used by the Association were calibrated in 1933 by the National Physical Laboratory. A more extensive calibration has since been made by the

author on the newer instruments, fitted with each of the three types of electrodes which have been used.

The main object of these tests was to obtain data connecting the peak voltage applied to the klydonographs and the size of the klydonograms produced by both pairs of each electrode type. It was also desired to obtain some idea of the probable accuracy of the instruments as peak voltmeters under service conditions. The following are the salient features of the tests:—

- (1) To simulate practical conditions, the field test-hut and the normal auxiliary equipment were employed.
- (2) The impulses were applied to the potential-divider

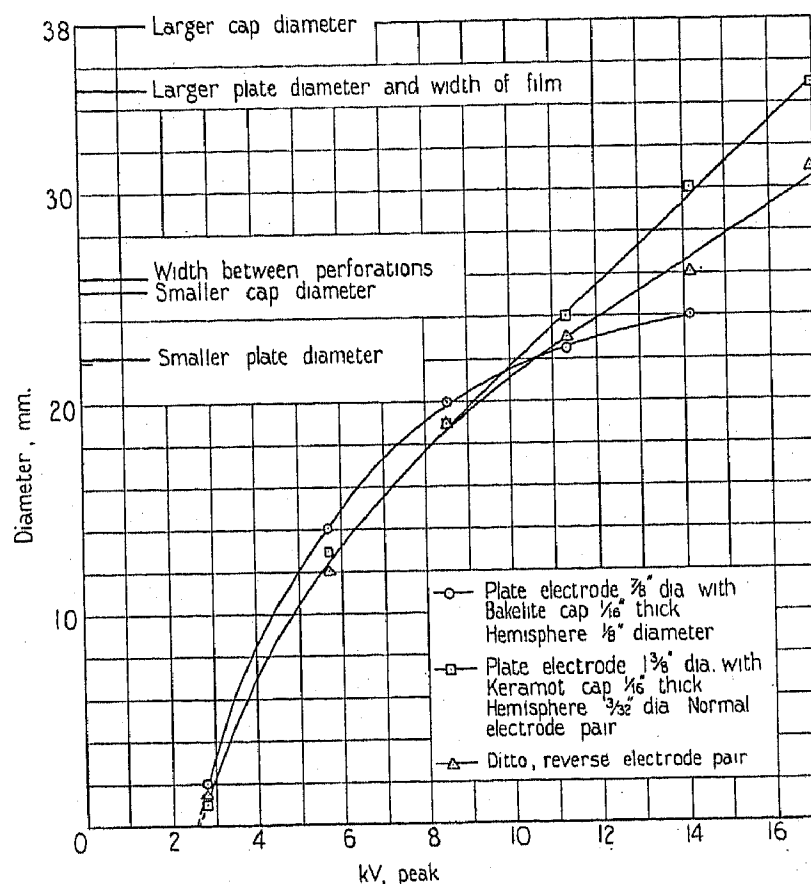


Fig. 13.—50-cycle calibration curves.

by means of a high-voltage impulse generator. A 1/50-microsecond wave was chosen, and both polarities were used.

(3) The wave form and peak voltage of the impulse applied to the divider were determined from cathode-ray oscillograms.

(4) After the tests the oscillograms and klydonograms were measured, and from the results obtained curves were drawn; some of these are shown in Fig. 18.

Circuit Arrangements.

The circuit employed is shown in Fig. 15. Within the test hut it was necessary to run busbars for tests in which several instruments were connected in parallel. To minimize the risk of voltage oscillations between instruments, loop inductances were kept as low as possible and a non-inductive damping resistance was connected in the high-voltage lead close to each instrument, its value being made as high as possible, consistent with not appreciably affecting the voltage across the electrodes. No indications of oscillations appeared in the figures obtained.

Fig. 16 (Plate 3) shows an oscillogram, taken during the

tests, of a typical impulse; it represents a positive 1.1/48-microsecond wave. In all, some 120 tests were made and about 60 oscillograms and 450 klydonograms were used in the calibrations.

Conditions of Test.

In general, the test conditions were made as nearly as possible identical with normal operating conditions. For example, silica gel desiccators were used in the instruments, but no attempt was made to control air temperature or pressure; these were, however, noted. The tests extended over some 4 weeks, and consequently both temperature and pressure were subject to variation. Since it is impracticable to control these variables under service conditions, the course adopted is justified. Film as used for recording was employed.

The electrodes used were as given in Table 2.

Tests Made.

Impulse voltages between approximately 2 kV and 17.5 kV were applied to the klydonographs. Generally groups of 9 impulses were applied, as by applying several impulses at each voltage to each instrument it was

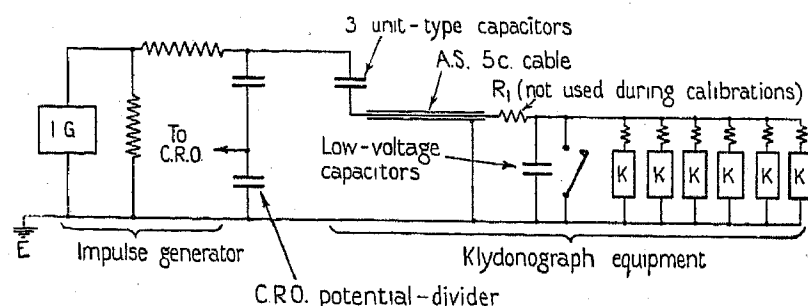


Fig. 15.—Circuit employed for impulse calibration.

possible to obtain curves of maximum, minimum and average figure sizes for each electrode type tested.

Results Obtained.

The results obtained were generally satisfactory and, although some of the figures exhibited unexplained defects, many excellent and regular figures were produced. A group of 12 of these is shown in Fig. 17 (Plate 4).

The klydonograms were measured using the technique described in Section (4)(b)(iii), any figures with obvious defects being omitted. The results were tabulated and analysed.

It was found that, in general, there was no difference between the ranges of figure sizes produced at a given voltage by two similar instruments connected in parallel. It was also found that coating the bakelite electrode-caps with celluloid had little effect on the klydonograms.

The figure sizes were averaged in each group. Curves were then plotted showing maximum, minimum and average figure sizes for the range of applied voltages; these curves are reproduced in Fig. 18. If a very large number of tests, with various types of wave, had been made at each voltage, these curves might have been slightly different, but it may be assumed with little error that the curves represent minimum, maximum and probable voltages respectively, corresponding to any given figure size.

Probable Accuracy of Voltage Estimation.

Figures given by some of the earlier investigators for the percentage possible errors indicate that any one result is probably accurate to within $\pm 15\%$, although errors as great as 50% are possible. It appears that these figures apply to the range of klydonogram sizes produced by a given applied voltage, but have been assumed to apply also to the range of voltage for a given size of klydonogram. Since the calibration curve is not a straight line passing through the origin, and since a klydonograph is more a means of estimating voltages from given klydonograms than of producing klydonograms from known voltages, the percentage possible error should preferably be associated with the voltage range covered by a given klydonogram size.

It was with this in view that, from the curves obtained, possible percentage errors in estimating voltage were calculated; for convenience, these possible errors were expressed as percentages of the probable voltages.

These calculations show that the possible errors arising

Table 2

Electrode arrangement	1	2	
Plate electrode diameter, in.	$\frac{7}{8}$	$\frac{7}{8}$	$1\frac{3}{8}$
Cap material	Bakelite	Bakelite, celluloid-coated	Keramot
Cap diameter, in.	1	1	$1\frac{1}{2}$
Cap thickness, in.	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$
Diameter of hemisphere, in.	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{3}{32}$

from positive figures should not exceed $+25\%$ or -20% for the $\frac{7}{8}$ in.— $\frac{1}{8}$ in. electrodes (either plain or coated) up to about 5 kV (probable), but may reach $+115\%$ or -60% for the higher voltages. Similar figures for the $1\frac{3}{8}$ in.— $\frac{3}{32}$ in. electrodes are $\pm 20\%$ up to about 7 kV, and $+40\%$ or -30% for the remainder of the range. Bearing in mind that the diameter/voltage slope of the calibration curve is considerably steeper for the latter electrodes, it is clear that their use permits greater accuracy of voltage estimation.

(iii) Measurement of klydonograms.

Many klydonograms are not circular or regular, and their measurement is both difficult and subject to individual judgment. A standard technique has been developed in an attempt to obtain greater consistency and thereby greater accuracy.

The film is viewed on the emulsion side by the reflected light from a screened bench lamp. Under these conditions the streamers comprising the figure appear matt and dark, whereas the surrounding film appears glossy and bright. The figure is rendered still more obvious by placing under the film a matt white card, and for purpose of measurement cards are used on which have been drawn circles with known diameters.

Briefly, the following apply:—

- (1) The circle should be chosen which just encloses the

entire figure. If, however, to include a small percentage of the streamer tips necessitates the use of a larger circle, these are ignored.

(2) Large figures are often oval in shape, possibly on account of the limit set by the film width and perforations. It is believed that this shape arises from shortening of the streamers lying across the film width rather than by extension of those lying more in the direction of film travel. When measuring such figures, therefore, more weight is given to the latter streamers.

the factors affecting their size and type, but the results so far obtained indicate that it is doubtful whether the time and labour involved would be justified. From what has already been done, however, the following points emerge:—

(1) 50-cycle calibrations cannot be satisfactorily employed for impulse-voltage estimation; they do, however, afford ready means of predicting the response to impulses very approximately.

(2) That the instruments in their present form are

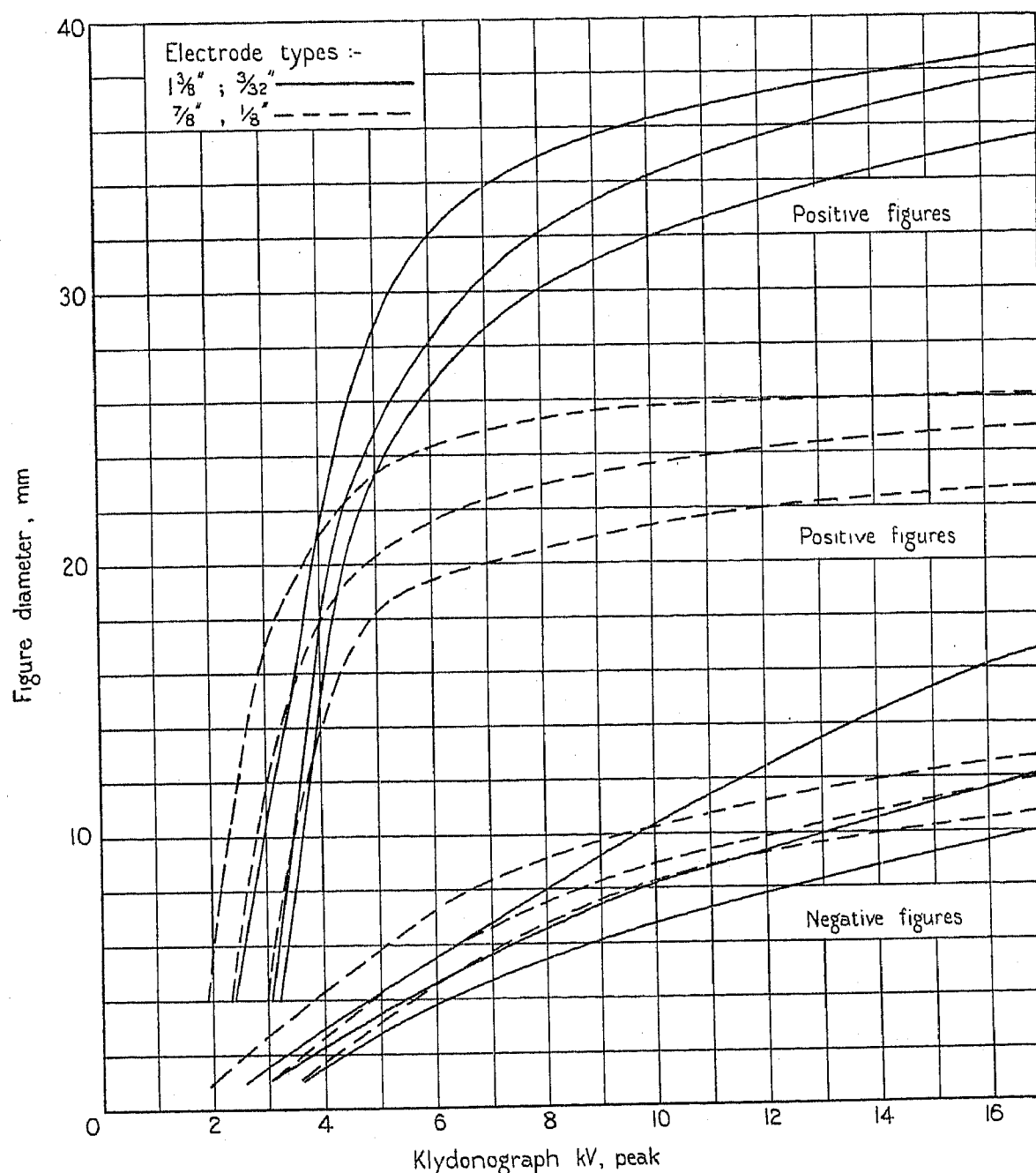


Fig. 18.—Impulse calibration curves. Positive and negative figures, positive 1/50-microsec. impulses. Two electrode types.

(3) The streamers of many figures are not of comparable lengths around the position of the electrodes during recording, and give the appearance of eccentricity. The cause of this is not known, but experience has shown that the measuring circle is best fitted so as to be concentric with the electrode positions.

(4) There appears to be no justification for measuring figures to closer limits than ± 0.5 mm.

(iv) Conclusions.

It is clear that much work could still be done in connection with the production of klydonograms and with

capable of recording, with reasonable accuracy, surge voltages between 3 kV and 15 kV.

(3) That it is doubtful whether this range can be increased without employing wider films, and larger electrodes and clearances.

(5) FIELD INVESTIGATIONS

(a) Chronological Résumé of Tests

The first recording took place in 1933 at three sites on an 11-kV line between Thornhill and Barugh, owned by the Yorkshire Electric Power Co. The operation of both

the klydonographs and the potential-dividers was unsatisfactory, and no records of surges were obtained.

In 1934, three klydonographs were installed on the C.E.B. 33-kV Rayleigh-Southend line. During this year the new instruments and the bushing-type potential-dividers were put into use, and the records showed considerable improvement. An interesting group of surges occurred on the 9th November, and the records are reproduced in Fig. 19 (Plate 5). Five negative surges and one positive surge were recorded, none of which exceeded 1.7 times normal voltage. It is thought that the disturbance was due to switching operations, although these were not confirmed by the Board.

Recording on this line was continued during 1935. In December the instruments were withdrawn for overhaul, no records of surges having been obtained during thunderstorms. Numerous records of switching surges were, however, obtained, including some during special tests on the 4th and 28th March, 1935.

During the same year, further recording took place on the Thornhill-Barugh line. The new instruments (in their original form) and unit-type dividers were used, with better results than those obtained previously. On the 24th September several surges occurred during a thunderstorm, the line being tripped out twice. The records obtained at one of the sites are reproduced in Fig. 20 (Plate 5). It will be seen that on each film are a number of superposed and irregular klydonograms, making measurement difficult and unreliable. It appears, however, that the highest surge voltage recorded is 2.5 times normal voltage. The multiplicity of figures may be due to repeated reflection of the incident surge, caused by the large number of points on the line at which the surge impedance changes.

In October, 1935, recording was started with three instruments in the south of Scotland. Unfortunately, shortly afterwards a severe gale overturned two of the huts housing the instruments, and recording was suspended. No surge records were obtained from these sites.

The work of improving the instruments, as described in Section (2), occupied 1936, but in 1937 three of them were installed at the C.E.B. Creekmouth transforming station, near Barking, and three more were installed on the C.E.B. 33-kV Rotherham-Doncaster line. In the latter case the unit-type dividers, the modified klydonographs and, for the first time, low-capacitance screened down-leads were used. The performance of both groups was very satisfactory, although the records from the Rotherham-Doncaster group were marred at intervals by spurious 50-cycle figures and intermittent stoppages. As mentioned previously, the cause of this was found to be combined wetness and pollution of the potential-dividers.

The line under observation was equipped with Petersen coils, and during their commissioning tests on the 9th May a group of 50-cycle figures was obtained. Prints of these appear in Fig. 21 (Plate 6). Records of surges were obtained during thunderstorms on the 21st May and the 15th July. Fig. 22 (Plate 3) shows the record obtained from the normal electrode pair at one of the sites on the latter date, the surge indicated being a positive unidirectional one, with a peak value of 3.9 times normal voltage.

No records of lightning surges were obtained at the Barking site.

Recording was resumed on the Rotherham-Doncaster line during 1938, and on three occasions surge records were obtained during thunderstorms. The surge voltages indicated were, however, only slight.

During 1939 further recording took place on the Thornhill-Barugh line. Only three minor surges were recorded during thunderstorms.

Fig. 23 (Plate 6) is a composite photograph of one of the sites in Scotland, and shows the potential-divider, test hut, and line and tapping connections. The tower shown is a tapping tower, and it will be seen that the top conductor of the circuit is unusually accessible.

(b) Results Obtained

(i) Explanatory notes.

It is not possible definitely to deduce from klydonograms whether a surge occurring on an energized line is due to lightning or to switching operations. It is as-

Table 3

Type	Group D	Group Y	Total
Positive	3	1	4
Negative	3	2	5
Oscillatory*	2	4	6
$\left. \begin{array}{l} < 2 \\ 2-3 \\ > 3\ddagger \end{array} \right\} \text{ times normal voltage}$	3	5	8
	3	2	5
	2	0	2

* Although the incident surge may have been unidirectional.
 † The highest value was 3.9 times normal voltage.

sumed that it is due to lightning if it occurs during a thunderstorm, and that it is due to switching operations if no storm was reported for the period concerned. In some cases, however, as during special switching tests, the origin of the surge is definite for all practical purposes.

If the incident surge be oscillatory, it will appear as such in the records, provided the peak voltages of both polarities are sufficiently high. On the other hand, an initially unidirectional surge may produce similar records if the circuit conditions of the line cause reflections of reversed polarity. In the following, the recorded indications are always stated, as it is rarely possible to differentiate between these two cases.

The magnitudes of the voltages indicated are given in terms of the normal voltage; this is the peak value of the nominal voltage of any phase wire to earth (i.e. 27 kV for a 33-kV line).

Very small figures appearing in the records are of no practical importance and are not reported. The upper voltage limit for such figures is approximately equal to the normal voltage as defined above.

(ii) Lightning surges.

No surges considered to be due to lightning were recorded on the Rayleigh-Southend line, on the lines in South Scotland, or at the Creekmouth transforming

station. Recording on the Rotherham-Doncaster line (Group D) and the Thornhill-Barugh line (Group Y) yielded 15. An analysis of these appears in Table 3.

(iii) Switching surges.

Numerous switching surges occurred, and an analysis has been made for the group of instruments recording on the Rayleigh-Southend line during 1934 and 1935. Of a total of 18, one surge was oscillatory, and 17 were unidirectional and approximately equally divided between the two polarities. It must be remembered, however, that a surge which appears from klydonograms to be unidirectional may actually be oscillatory, provided the damping is sufficiently great for only the first loop to be recorded.

As regards magnitude, the peak values of 13 of the surges did not exceed 1.5 times normal voltage, and none exceeded twice normal voltage.

(6) CONCLUSIONS

(a) Apparatus

(i) Klydonographs.

Certain conclusions have already been stated in Section 4(b)(iv).

To these should be added the following points:—

(1) Close attention to mechanical and constructional details is essential if reliable operation is to be ensured. Typical items are the sprocket wheels, couplings and allowance for deformation of the cases, which might with advantage be constructed of some material other than wood.

(2) The phenomenon of film seizure at the electrodes due to sustained over-voltages is important. It is suggested that when testing klydonographs they should be run under normal conditions, but that the effect of sustained over-voltage be ascertained. Humidity affects the phenomenon, which is most noticeable after prolonged drying.

(3) Great care should be exercised in the construction of the electrodes. Those developed by the author were checked for accuracy at each stage, and it is probable that the degree of uniformity achieved is largely responsible for the greater accuracy of voltage estimation made possible by their use.

(ii) Potential-dividers.

Certain desirable features of capacitance potential-dividers have been stated in Section 3(b). The investigation has yielded the following additional points:—

(1) The impulse-voltage ratio of the potential-dividers should be stabilized by reducing capacitance variations to a negligible quantity. The chief cause of such variation is the tapping lead, and satisfactory stability can be obtained by screening this.

(2) It is desirable also to stabilize the 50-cycle voltage ratio. To do so it is necessary in all cases to maintain high values of line-to-tapping and tapping-to-earth insulation and leakage resistances, as by sealing certain terminals.

(3) Instability of the type described in item (2) may occur with unit-type potential-dividers under conditions of combined pollution and wetness. It may be reduced to a satisfactory value by suitably insulating the capacitor junctions and the tapping point from the bolting flanges.

(b) Records

(i) Lightning surges.

The number of surges recorded during thunderstorms is insufficient to permit generalization on the nature of lightning surges on transmission lines. Such sparse results are normal in this country, however, and from the few surges which have been recorded it may tentatively be concluded that the majority of lightning surges do not exceed 3 times the normal voltage, and have no harmful effect on the line or on the apparatus connected thereto. Since, however, damage due to lightning surges does occur, the figure given must not be regarded as approaching the upper voltage limit, which is, in fact, governed mainly by the insulation of the line. It is obvious, therefore, that no direct strokes to the line occurred near to the recording sites. The results to date do not indicate a preponderance of either positive or negative surges. It may be concluded, however, that the majority of lightning surges are unidirectional, although they may undergo reversal by reflection. It appears that it is not uncommon for a thunderstorm to occur near a line without producing any appreciable surge voltages on it.

(ii) Switching surges.

Switching surges are numerous; they are usually unidirectional (or oscillatory but highly damped), approximately equally divided between the two polarities, and limited to not more than twice normal voltage.

(7) ACKNOWLEDGMENTS

The author wishes to thank the Electrical Research Association for permission to publish this paper, and to record the Association's appreciation of the co-operation of the Central Electricity Board and the Yorkshire Electric Power Co. in the field investigations.

The author also wishes to thank Mr. H. M. Lacey, Chief Engineer, Surges and Transformer Department, for his helpful advice throughout the investigation, Mr. E. L. White for his valuable assistance with the practical work thereof, and Mr. W. G. Hawley for his help with the impulse calibration.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 5TH APRIL, 1940

Mr. C. W. Marshall: The paper would be improved if the many unimportant and trivial details which it contains were omitted. Satisfactory parts of the paper are those dealing with calibration and potential-division. There, a little expansion might have been justified.

The underlying objective is to find means of preventing

breakdowns of equipment and outages of circuits in transmission systems, due to voltage surges, and the klydonograph work is a fairly important section of a general investigation which is being carried out by the E.R.A. with that end in view. The rate of progress in the klydonograph work seems to have been extremely

slow, and the results which are presented here are a poor return for the expenditure.

The author mentions that the number of klydonograph records obtained was disappointingly small. I consider that it would be much more useful if he estimated the probable number of surges which occurred during the recording period, and compared this number with the actual number of records obtained, thus indicating objectively the efficiency of the klydonograph work.

Mr. H. M. Lacey: The present status of the klydonograph as a measuring instrument can best be appreciated by considering its history, which extends over a total period of more than 150 years. It began with the discovery by G. C. Lichtenberg in 1777 that the discharge of a Leyden jar between electrodes separated by a glass plate, on which fine powder was scattered, produced well-defined patterns. Over a century later, in 1888, two investigators, J. Brown and E. J. Trouvelot, discovered independently that similar figures could be produced on a photographic plate. It was not until 1923 that Peters, in America, used the phenomenon to record surges; during the next few years many papers appeared in which extravagant claims were made as to the information afforded by the new apparatus. When it was found that these extravagant claims were not justified, and that not only was it very difficult to construct a klydonograph which would run unattended for periods of a week or more but also that the very simple potential-dividers advocated by the first users were most unsatisfactory, there was a tendency to discredit the method entirely. This stage had been reached when the E.R.A. began an investigation of surge phenomena. The high-speed cathode-ray oscillograph had been developed, but the chance of obtaining lightning-stroke records in Great Britain was not considered great enough to justify the wide use of so expensive an instrument. A paper by Melsom, Arman and Bibby* describing the use of klydonographs in a successful investigation of specific surge troubles had appeared a short time previously, and it was decided to start the investigation with instruments exactly similar to those used by these investigators. It was soon found that the klydonographs and potential-dividers suffered from many mechanical and electrical defects which rendered them unsuitable for unattended use. New instruments of generally similar but much more robust design were obtained, and new types of potential-divider were developed, but some of the faults still persisted. The author of the present paper had to exercise a great deal of patience to trace all the numerous individual faults to their source and to rectify them.

The klydonograph has suffered perhaps as much from its advocates as from its detractors, and the paper serves a useful purpose in indicating the defects to be avoided and the extent of the information which can be expected from this class of instrument.

Dr. W. Wilson: One of the most useful functions of the klydonograph in industry is the detection of surges, which are habitually made the scapegoats for breakdowns in all sorts of situations. I have used it for investigating troubles associated with a power-supply substation, high-voltage control gear for a mine hoist, mercury-arc rectifiers, power-factor condensers and a

number of other types of equipment; and not only were no surges detected in any of these, but owing to the very useful negative information given by the klydonograph the real cause of the trouble was discovered in all cases but one. Perhaps I may refer to the case of the rectifier, since this investigation illustrates the essential simplicity of the instrument. It was a 12-phase unit, and as the alleged surges might have occurred in any of the phases, our supply of klydonographs was over-strained. We happened to have in stock, however, 12 empty lantern-slide boxes made of cardboard. A $3\frac{1}{4}$ -in. square brass plate was placed in each of these, and a strip of flexible brass fixed to the inside of the lid with a hemispherical electrode soldered on the end, so located that it rested just upon the centre of the film. An ordinary photographic plate was then inserted, an elastic band slipped round the box to keep the lid on, and the instrument was complete. We have found the sensitive-plate type of klydonograph easy to use and very reliable; and, in spite of the changes introduced by outdoor investigations and continuous recording, I am a little perplexed at the frequent references in the paper to difficulties in operation.

It could have been wished that Mr. Candler had inserted in his paper a reference to the paper by Messrs. Melsom, Arman and Bibby. Had he done so, many of his introductory remarks could have been omitted.

He has used two forms of potential-divider which are new to me, and which I suspect may have been the source of inaccuracy. A usual method of forming a potential-divider, which has been found satisfactory both in this country and in America,* is to suspend a link insulator from the overhead line and to tap the klydonograph off the last link. It should be borne in mind that the potential-dividing is proportional not to the capacitance but to the reactance. Now a potential-divider of the capacitance type also possesses inductance, but the reactance due to it is negligible at ordinary frequencies. Overhead-line surges, however, are of abnormally high frequencies, and may alter the conditions considerably. For example, if it is assumed that the wave front is 1 microsecond, and that this represents one-quarter of a cycle, then the frequency is 250 kc./s., and the capacitance reactance is reduced to 0.0002 of what it is at 50 c./s., while the inductive reactance is multiplied by 5 000. With the link type of capacitance potential-divider, where the condensers are in a straight line, not only is the insulation resistance proportional to the length and therefore more or less to the capacitance, but it is possible to take off the tapping at such a point that the lengths of straight conductor are also proportional to the ratio by which it is desired to multiply the determinations. I therefore consider the straight-line arrangement much less likely to introduce inaccuracy than the types adopted by the author. Reference to Fig. 23 (Plate 6) shows that the down-lead to the potential-divider will have a great deal of inductance associated with it, causing the potentiometer to increase the readings unduly. I should like to ask whether the author considered using a resistance type of potential-divider, as is done in the surge generator. Both liquid and wire-wound resistors are employed in this apparatus for very high voltages; while resistance-type

* *Journal I.E.E.*, 1930, 68, p. 1476.

* See, for example, E. S. LEE and C. M. FOUST: "Measurement of Surge Voltages on Transmission Lines due to Lightning," *Transactions of the American I.E.E.*, 1927, 46, p. 345, Fig. 21.

potential dividers are also used in high-power test stations, and for other quite onerous duties.

It is not clear why Fig. 23 is described as a "composite photograph," since there does not appear to be anything composite about it.

I should ascribe the "snatching" which was noticed by the author to the fact that he has reversed the functions of the two motors. The main motor, which ought to be doing the driving, with the forward part of the sprocket teeth in contact with the film, is in fact being used as a brake; and apparently the take-up motor, the usual purpose of which is simply to absorb the slack and ensure that the film is wound on to the drum, is being employed to do all the pulling. In the cinematograph projector, which has a somewhat similar type of feed, the take-up motor is represented by a metal belt which actually slips, so that it just keeps the film tight.

In Fig. 19 (Plate 5), two records and two discontinuities are shown. What is the reason for these?

When dealing with the measurement of klydonograms, the author apparently disregards any "rays" that go beyond the point where it is conjectured they ought to stop. Surely this is not a very precise method of measurement. It has always been my own practice to measure the longest ray, and this I have understood to be the usual method. To secure a fair value, I consider that one must either do this or else measure all the principal rays and take the average value.

It seems to me that the "oscillatory" surges mentioned by the author are due either to switching operations or to lightning striking the transmission line, whereupon the line starts to oscillate at its natural frequency. If the circuit is heavily damped, e.g. if the resistance is round about the critical value $2\sqrt{L/C}$, either it will not oscillate at all or there will be a damped train of a few vibrations. An investigation was made in America by F. W. Peek,* who analysed all the surges recorded on a certain line in a given period, and the conclusion reached was that no surge lasted more than six cycles, while most last only one half-cycle, or one major half-cycle followed by a much smaller loop in the opposite direction. The question whether the surges are oscillatory thus depends on the line and not on the originating impulse. The author mentions that they may be oscillatory and that the second half-cycle may not be recorded. This is probably true in the case of a positive surge, because the following (negative) figure will be on a much smaller scale; but if the first half-cycle figure is negative, then there is a big chance of the positive loop being recorded.

Mr. P. W. Baguley: This paper has been of particular interest to me, because I have just returned from doing very similar work abroad, where almost identical instruments were used. They proved almost free from trouble, except for a few faults similar to those described by the author. Two of the unit-type condensers suffered from internal moisture, and the affected phase had to be disconnected from the supply during their repair. The wood cases of the instruments were not entirely satisfactory under tropical conditions owing to shrinkage in the extremely dry atmosphere; this bears out the author's conclusion that the use of wood should be avoided.

"Snatching" proved troublesome, few films being free from that fault.

In view of the author's conclusion that the accuracy of the electrodes is most important from the point of view of securing consistent results, stainless steel hemispherical electrodes are not ideal. Corrosion and pitting occur near the point of contact, and any attempt to remove the marks by polishing will affect the accuracy of the contour. Would the additional cost of using platinum for these points be justified?

It is thought to be of advantage to time-mark the instruments daily rather than weekly, if it is possible to do so. The instrument voltage can be checked at the same time to indicate whether electrical leakage is occurring. From the time marks a record of the instrument rate can be kept, so that the effects of any stoppage are restricted to one day only. In addition, the subsequent analysis of the record is a much easier matter.

Dr. A. N. Arman: One of the reasons why it is more difficult in this country than in America to work these instruments and their dividers is that in America the climate is much drier and exposed potential-dividers can be used without risk of leakage troubles. The dividers that Mr. Melsom, Mr. Bibby and I designed were of very low capacitance, but they were totally enclosed and free from troubles due to insulation leakage; any leakage which occurred came quite outside the electrostatic field of the divider. The only problem was how to get a screened lead of sufficiently low capacitance to connect to the very low-capacitance secondary electrode.

I think I detect in the paper a note of disappointment that so few records were obtained; had the author used the instrument in the more sensitive condition that we did, namely with a very small normal-voltage line, just on the threshold where the instrument starts to record, he would have obtained many other interesting records apart from those due to lightning. I agree, however, that such records are more difficult to interpret.

I am interested in the author's description of what he calls the "wringing" of the film to the electrode. We did not encounter this effect, presumably because we used ebonite insulation instead of bakelite. The phenomenon is possibly associated with the Johnsen-Rahbek effect, a demonstration of which was given before The Institution in 1921.

We too had a good deal of trouble with the "hairy" line effect, and we found by later experiments that it could also be produced by "snatching" of the film, associated with a slight "bounce" of the electrode. When the film advances with a jerk, the field due to the electrode has to be built up on a fresh portion of the area, and if the electrode is advanced sufficiently quickly, particularly when it bounces, it actually produces the same effect as a slight surge. The effect is usually of rather an indefinite character and gives rise to "hairs" in one direction only, presumably due to some slight irregularity of the point electrode.

The author found that when the klydonograph figures are large they are often elliptical in shape, with the major axis in the direction of the film. We also experienced that effect, and we think it is due to slight upward curling of the film at the edges of the electrode. The author's instrument attempts to overcome that by

* "Lightning and other Transients on Transmission Lines," *Transactions of the American I.E.E.*, 1924, 43, p. 1208.

pulling the film down. We tried to do the same thing, but the difficulty is that the film is very stiff.

The author remarks that the electrodes with Keramot caps gave greater accuracy in the recording of voltages. I should like to know the reason for this.

The calibration curves in Fig. 13 show a distinct difference between the normal electrode pair and the reverse electrode pair. This would seem to indicate that the electrostatic-field relations of the two pairs of electrodes were not the same. We encountered the same phenomenon in our early work with these instruments, and we dealt with it by putting a plate across the two top electrodes to balance the capacitance conditions. It appears that the necessary correction has not been completely carried out in the author's instruments.

Mr. F. R. Perry: I am interested in the author's account of mechanical troubles associated with klydonographs, because about 6 years ago I was associated with the development of a rather similar type of instrument and encountered the same kind of difficulties. On one occasion we installed our own instrument on a power-supply system and over a period of weeks it registered a large number of surges. The system engineers did not believe that these surges had actually occurred, and in the end we had to admit that they were right. We found that, owing to a mechanical defect, the film would sometimes hesitate for a short time, with the result that the normal-voltage line broadened out into a small circular mark, having the appearance of a small surge figure, but which in reality was a fogging mark. This experience showed that incorrect mechanical operation was liable to give misleading results from the electrical point of view.

I agree with the author in regard to the type of condenser to be used as a potential-divider. I do not believe strings of insulators should be used for this purpose as I am sure that the capacitance of such strings is too small for reliable results to be possible, unless the klydonograph is calibrated with the divider exactly as it is used on site. Even if this is done, the divider ratio can be badly upset owing to leakage caused by rain and dirt deposits.

The calibration curves in Fig. 18 show a very high sensitivity over a small voltage range and a lower sensitivity over a larger voltage range. If the author had used a sharper point electrode I think that he would have found a more linear relationship between the size of figure and the voltage producing it, and this would have been more convenient for interpreting field records. With a sharp point electrode, mechanical difficulties might be encountered, due to the point scoring the film, and an alternative solution might be to use a small wheel with a sharply-radiused edge. This type of electrode might give a figure of elliptical shape, as the radius of curvature in one direction would differ from that in the other, but this feature might not matter, because it could be taken account of in the course of calibration.

Using klydonographs of the type described by the author we obtained a number of lightning records in Nigeria. They varied considerably in size but, according to the calibration curve, not very much in voltage. We had a 3-phase bank of klydonographs on one feeder and a 3-phase bank of oscillographs on a parallel feeder. With the aid of the oscillograms we could interpret the

klydonograms much more precisely than would have been possible otherwise, and the klydonograms confirmed certain features which seemed contradictory on the oscillograms.

It may be mentioned at this stage that even with a unidirectional surge, completely free from oscillations, it is possible to get positive and negative figures recorded on the same film from one pair of electrodes. Thus a positive surge gives a large positive figure with (on the photographic negative) a dark centre, representing a sort of negative "back" figure due to the decay of the voltage wave. The effect can be seen even more clearly with a negative surge, which gives its own characteristic straight filaments produced during the rise in voltage of the impulse, together with curled filaments which are positive in character, and are caused during the decay of the impulse. These back figures may, I think, be useful in interpreting results, because they are the more intense the steeper the wave tail, and one would expect to find them most sharply defined where there was flashover on a line. The klydonograms are quite different from those caused by oscillatory surges because, for example, the back positive figure produced by a negative unidirectional surge is confined within the dimensions of the negative figure first produced. A paper recently published by Merrill and von Hippel,* who have been observing klydonograph figures in various atmospheres and at various pressures, shows some beautiful back figures and explains how they are produced.

The instrument of this type which we developed, quite independently, used a 35-mm. cinematograph film, and eventually included a timing motor and a take-up motor. The recording range was from 2.5 kV to 15 kV, which agrees closely with the author's figures. We obtained rather higher flashover figures for the instrument than those quoted by the author. One may want to record voltages as high as 10 to 15 times the normal working voltage. The author refers to the figure of 6 times, and I agree that most of the surges obtained are within this limit, but higher values might be expected occasionally.

A suggestion which might be worth investigating was made in the discussion on the paper by Messrs. Melsom, Arman and Bibby some years ago; it was that if a d.c. voltage of, say, + 3 kV was impressed between the electrodes and a + 3-kV surge was then applied, the klydonograph figure produced would be of the size of a + 6-kV surge figure. If that is true, it means that when there is a normal alternating voltage on the power line, then, as it is not known at what part of the wave the surge figure is produced, the effect of the instantaneous value of the 50-cycle voltage cannot be calculated. On a 33-kV line there would be a maximum discrepancy of ± 27 kV (peak), which is rather considerable if one is trying to estimate the surge value from the klydonograms obtained. It would be easy to investigate this problem in the laboratory, using controlled or synchronized impulses on a 50-cycle wave.

In Fig. 7(c) (Plate 2) the author shows the klydonograph figure for Petersen-coil operation. Surely if the coil had operated correctly the normal-voltage line would have continued right across the record; because the object of a

* F. H. MERRILL and A. VON HIPPEL: *Journal of Applied Physics*, 1930, 10, p. 873.

Petersen coil is to maintain the voltage supply without interruption. I should like to know the circumstances which caused the normal-voltage line to disappear in the middle of the record.

Mr. O. Howarth: The Lancashire Power Co.'s first surge investigations were made because, when asked to explain the failure of an insulator in the principal power-station, the manufacturers had said "Of course, it must have been due to one of those terrible surges to which your system is peculiarly subject. What you have to do is to prevent such surges occurring." We did not think that they did occur, and to settle the point we made investigations. We employed a plate-type klydonograph, with a $8\frac{1}{2}$ in. $\times$ $6\frac{3}{4}$ in. plate which we put on a metal tray running on wheels inside a box, and which was drawn along by means of a clock outside at the rate of $\frac{1}{4}$ in. an hour. With this we were able to get a 30-hour record, and as the instrument was installed at the station we could afford to pay daily attention to it. For the points resting on the top of the plate we used ordinary meter pivots, which seemed very satisfactory; we weighted them suitably so as to get a reasonable pressure on the plate.

We put all three phases on one plate. In this connection I should like to know whether the author used a klydonograph on each phase at every position. He refers to one figure only, as though only one phase was recorded, and Fig. 23 (Plate 6) shows only one potential-divider.

We found that whenever a surge occurred it burned the photographic film away, and I am interested to know whether that burning has anything to do with the "snatching" in the film-type klydonographs. When using plates we did not suffer any trouble due to snatching.

Our investigation extended from September, 1930, to September, 1931, and it cost us under £500, including the construction of the klydonographs and potential-dividers. The plate-type klydonograph seems to have advantages, one of which is that the figure can be seen under the red light during development.

In the course of our experiments three supply systems, those of the Lancashire Power Co., the Manchester Corporation, and the Rochdale Corporation, were all coupled together. When the klydonograph record indicated that a surge had occurred we were able to obtain details of trips or switching operations by telephoning inquiries to each of the other undertakings. During the year we recorded about 250 surges, and succeeded in tracing the cause of nearly every one of them. The klydonographs were installed in the Kearsley power station, and connected to the busbars. At that time about 100 miles of 33-kV cable were connected, and a certain amount of overhead line, but the nearest overhead line was 10 miles from the station; so that the conditions which we were investigating were rather different from those referred to by other speakers. The star point of the system was earthed through a resistor which limited the current on a dead earth fault to 240 amp.

We were able to draw fairly definite conclusions from the investigation. We realized, of course, that the klydonograph is rather a crude instrument, but at the same time we were satisfied that the maximum surges which occurred on our system were of less than 100 kV, which is less than the voltage that the insulators were

supposed to withstand. We concluded that when an earth fault occurred on one phase of a feeder the surge was caused by the energy stored in the capacitance of the other feeders discharging into the fault; and naturally the energy from many of the feeders had to discharge through the inductance of the Kearsley station busbars.

Prof. J. T. MacGregor-Morris: I was interested to hear what Mr. Lacey had to say about the historical development of this subject. In addition to the workers whom he mentioned, reference should be made to Prof. Pedersen of Copenhagen, because he has produced what is in my estimation one of the most extensive studies of the klydonograph that has been made up to the present.

Dr. Arman has rightly referred to A. Johnsen and K. Rahbek's work,* and I think that the work of H. M. Barlow† should also be remembered in this connection. Both Johnsen and Rahbek and Barlow have shown that the friction between two electrodes is greatly altered on applying the voltage if one of them is made of certain high-resistance conductors (i.e. of rather leaky insulators).

Reference has already been made to the question of why Keramot was substituted for bakelite in the author's experiments. If the author could state the series of materials he has tried and why they failed, it might be a useful guide for other investigators.

Mr. J. L. Candler (in reply): I am interested to have the opinions and suggestions of other investigators, and am grateful to them for the accounts of their experiences with klydonographs.

Mr. Marshall has referred to "unimportant and trivial details," which he considers should have been omitted from the paper. It seems fitting to record that the relatively slow progress made in the early stages of the investigation was entirely due to a failure to appreciate the importance of certain constructional details, and that it was not until each one was accorded its proper significance that the causes of faulty operation were traced and remedied. It was considered that an account of this work might appropriately interest the Meter and Instrument Section of The Institution. That this is so is confirmed by the trend of the discussion, which also supports my view as to the importance of the apparently trivial details, and I take this opportunity of stressing conclusion (6) (a) (i) (1) for the benefit of those who might otherwise be misled. The inclusion of detail in this paper is justified in that it is intended as a guide, to save other investigators a repetition of such work.

At the outset, a study of the published information on this type of research made it fairly obvious (a) that recording klydonographs were liable to "snatching" trouble, and (b) that this motion could produce records which might be interpreted as due to surges [see Figs. 4(a) and 4(b), Plate 2]. This interpretation has been confirmed by two speakers (Messrs. Arman and Perry). The simple klydonographs which Dr. Wilson describes should certainly be both easy to use and reliable, as he has avoided the difficulties introduced by the two factors which he mentions—namely outdoor investigation and continuous recording.

I cannot agree that a potential-divider formed by a series of normal insulators is suitable for use in this country—a view which Mr. Perry substantiates. More-

* *Journal I.E.E.*, 1923, 61, p. 713.

† *Ibid.*, 1924, 62, p. 133.

over, calculations of relative capacitive and inductive reactances based on Dr. Wilson's figures show that with the E.R.A. potential-dividers the inductive reactance has a negligible effect on the voltage ratio. There is much to be said for a capacitance-type divider, provided the effects of inductance and leakage resistance are suppressed as far as possible, and also provided the capacitance value is made high enough to mask the effect of variable stray capacitances, but not so high as appreciably to affect the impulse voltage. The possible use of resistance-type potential-dividers had been considered, but it was decided that, although they are in common use in indoor testing installations, they were unlikely to be as satisfactory as capacitance-type dividers for outdoor use, and might even prove impracticable.

Dr. Wilson is correct in saying that the take-up motor supplies the whole of the tractive effort. This is preferable to allowing an indeterminate division of load between the two motors, as generally appears to be the case. Even if a slipping-belt drive for taking-up is employed, there can be no certainty that the sprocket wheels will do the driving; they may restrain or drive, according to the particular conditions obtaining.

In Fig. 19 (Plate 5) a pair of records from one instrument is shown. Actually, there are more than two discontinuities, caused by the line being de-energized.

The method suggested in the paper for the measurement of klydonograms was evolved after much experience and consideration. It is quite possible that an average value obtained from measurements of all the principal streamers would give slightly greater accuracy, but this method seems unjustifiably laborious. The most important thing is to use the same technique for measuring both the calibration and the service figures.

Dr. Wilson's remarks pertaining to oscillation of the line as a whole, as a result of lightning, would apply only if the line were very short compared with the length of the impulse wave (approximately 1 000 ft. per microsec.), and this appears seldom to be the case. In practice, if an aperiodic travelling wave is produced on the line the potential at a point on the line may appear to be oscillatory on account of reflections. Contrary to Dr. Wilson's concluding statement, the recording of damped oscillations is not dependent on the polarity of the first loop, as two pairs of electrodes are provided.

In describing his experiences in Nigeria, Mr. Baguley mentions that even stainless-steel electrodes are liable to corrode. We have, however, found this material to be best, and suggest that it would be preferable to replace the electrodes periodically rather than to experiment with platinum. I agree that more frequent time-marking is helpful.

Both Dr. Arman and Prof. MacGregor-Morris attribute the film "seizure" to an electro-mechanical effect described at some length by Johnsen and Rahbek, and later by Barlow. Whilst they may be correct, an element

of doubt is introduced, partly by the necessity for a high voltage-gradient across a very short gap, and partly by a time-lag which we observed. The latter was sometimes of the order of many minutes, whereas the normal effect appears to be almost instantaneous.

The same two speakers both raise queries regarding the newer electrodes with Keramot caps. This material was found to give satisfactory results, but there may be other materials which are equally suitable. The advantages which result from the use of the newer electrodes are probably due to a difference in size which improved the shape of the calibration curve, and greater manufacturing accuracy and control, which reduced the spread of the results for positive figures (see Fig. 18).

The suggestions put forward by Mr. Perry for further electrode improvements are interesting. We have already made some preliminary tests with small wheels in place of the hemispherically-ended electrodes, but the results have not been encouraging. One objection is that it is more difficult to estimate the time of occurrence of the surge.

I am aware of the production of so-called "back" figures, but should hesitate to employ them for deriving information, although they might, perhaps, confirm facts already known. All the more spectacular figures in the paper by Merrill and von Hippel were obtained at increased pressure and, apparently, by enlargement.

There is little to be gained by making the flashover voltage of a klydonograph appreciably greater than the maximum voltage which can be recorded. It would, however, be useful if the ratio of maximum to minimum recording voltage could be increased beyond the value of 6 mentioned. This figure does not, of course, limit the highest line surge voltage which can be recorded, which is dependent also on the potential-divider ratio employed.

Mr. Perry mentions a possible effect of the superposition of surges on normal alternating voltage. If the size of the resulting figure is dependent upon their combined value, it would mean that all estimates of the surge component are subject to a tolerance of plus or minus the normal voltage. On the other hand, this is not as serious as it at first appears, since (a) the line insulation and terminal apparatus would actually be subjected to the voltage recorded, and (b) the effect would be proportionately less with the higher surge voltages, which are the more important ones.

In all the records reproduced, time is represented as progressing from left to right; this will, I think, answer Mr. Perry's query regarding Fig. 7(c).

In reply to Mr. Howarth, the instruments were connected one to each phase at only one site (Creekmouth transforming station). In other installations the most usual arrangement was to connect three instruments to different points on the uppermost phase wire. As regards burning, we did find that after prolonged stoppages in the early days the film between the electrodes had become charred, but it was never ignited.

THE DEVELOPMENT OF A PRE-STRESSED ("TOUGHENED") GLASS INSULATOR

By P. M. HOGG, B.Sc., Member.*

[Paper first received 29th November, 1939, and in revised form 8th January, 1940; read before the TRANSMISSION SECTION 10th April, and before the MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 18th March, 1940.]

SUMMARY

The first part of the paper briefly describes the manufacture of glass. This description is followed by a discussion of the development of strain in cooling glass, and "toughened" glass is shown to be glass which has been so cooled as to produce a state of high compression in the surface layers. An account is given of the application of toughened glass to the manufacture of power-line insulators, and the paper concludes with a summary of the tests made during the development period.

(1) GLASS

Definition

Although glass is such a common thing, it is difficult to define. One early writer describes it as a "concrete juice," another as a "stone," and a third, writing in 1662, notes that "the workmen, when it is in a state of fusion, call it 'Metall'." It is interesting to note that glass-makers still do so to-day.

The following definition of glass, given by Morey, is perhaps one of the best:—

"A glass is an inorganic substance in a condition which is continuous with, and analogous to, the liquid phase of that substance, but which, as a result of having been cooled down from fused condition, has attained so high a degree of viscosity as to be for all practical purposes rigid."†

According to this definition, the property which distinguishes a glass from other substances is that with decreasing temperature it can pass from a liquid to a state which may be regarded as a solid with a continuous increase of viscosity and without the discontinuous change associated with crystallization.

A glass is sometimes defined as an undercooled liquid because, on being cooled down from high temperatures, it passes through a temperature range in which, owing to its composition becoming unstable, crystals of certain compounds would separate out if it did not undercool and keep in the liquid phase during the time taken to reach a temperature at which its viscosity is high enough to prevent crystal development.

Glass, however, cannot be held for any length of time within this temperature range in which the viscosity, though high enough to delay crystallization or "devitrification," is not sufficiently high to prevent crystallization indefinitely.

Glass cannot be defined on the basis of chemical composition. There are many glasses, each with its own composition and peculiar properties.

* Messrs. Pilkington Brothers, Ltd.
† G. W. MOREY: "Properties of Glass."

Composition

All commercial glasses are composed of a mixture of oxides, of which silica is almost invariably one.

The chosen composition depends on the required properties of the finished glass, but the choice is limited by manufacturing considerations. The more important of these considerations are:—

(a) At a commercially obtainable temperature (say 1500° C.), the viscosity of the glass must be low enough to enable it to be "fined" in a reasonable time. "Fining" is the freeing of the glass from the bubbles produced partly by the air and moisture entrained in the raw materials and partly by the gases liberated by chemical reactions during the formation of the glass.

(b) At a temperature above its devitrification temperature the viscosity of the glass must be high enough, and the change of viscosity with temperature low enough, to enable it to be worked (i.e. blown, drawn, rolled or moulded, as the case may be).

(c) At, and immediately below, its devitrification temperature, the viscosity of the glass must be high enough to reduce the rate of crystal development to a very low value. The composition of a typical commercial glass with good weathering properties is:—

Silica	SiO ₂	72.0 %
Calcium oxide ..	CaO	10.3 %
Magnesium oxide ..	MgO	2.8 %
Alumina	Al ₂ O ₃	1.0 %
Sodium oxide ..	Na ₂ O	13.5 %
Sulphur trioxide ..	SO ₃	0.4 %

The raw materials required to produce this glass are:—

Sand (dry)	56.6 %
Limestone	9.1 %
Dolomite	10.8 %
Felspar	4.0 %
Soda ash (sodium carbonate)	13.8 %
Salt cake (sodium sulphate)	5.7 %

Melting

While glass has been made for thousands of years, the expansion of the industry, which began with the seventeenth century, may perhaps be said to mark the beginnings of its modern manufacture.

For many centuries before the Christian era, the mixture of raw materials was melted in a small clay crucible heated in a primitive wood-fired furnace, and special glasses are still made in essentially the same way, although on a much larger scale.

The small wood-fired furnace gradually developed into

a gas-fired regenerative furnace, holding as many as 20 fireclay pots, each containing over 3 000 lb. of glass, but the mass production of glass is now almost entirely carried on in a gas-fired regenerative tank furnace. In this type of furnace, a cross-section of which is shown in Fig. 1, the manufacture of glass is continuous, the raw material being introduced into the "melting end" and the finished glass withdrawn at the "working end" of the tank 24 hours per day.

The intimately mixed raw materials interact at the high temperatures obtaining near the melting end, to form glass which circulates in the tank for a very considerable time before finding its way to the low-temperature working end. During this time the glass is gradually fined and rendered homogeneous.

The tank is constructed with large fireclay blocks and is roofed over by a low arch of silica brick.

By means of a set of ports, producer gas and air, each preheated by passage through a separate regenerator, are admitted into the space between the surface of the glass and the arch along the melting end of one side of the furnace.

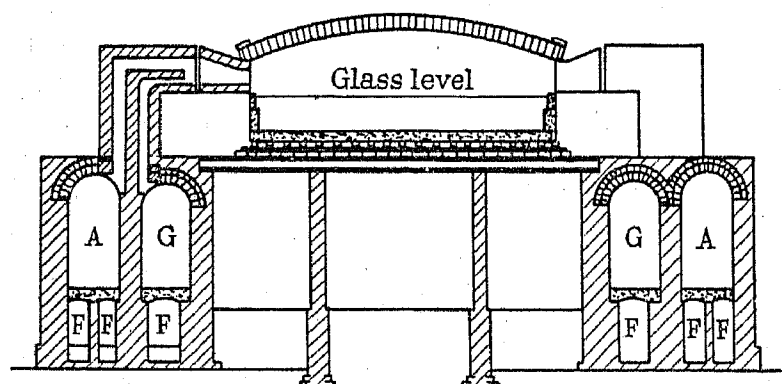


Fig. 1.—Section through melting end of glass tank furnace.

A.—Air regenerator.
G.—Gas regenerator.
F.—Flue.

The resulting long slow-burning flames heat the arch to a white incandescence, and the gaseous products of combustion and of the decomposition of the raw materials are drawn out through the corresponding set of ports and regenerators on the other side of the furnace by a tall chimney.

Every 20 minutes the "gas and air inlet" and the "chimney pull" connections to the regenerators are reversed, in order to preheat the incoming gas and air by the heat recovered from the outgoing gases during the previous "reverse."

The largest tank furnaces in use to-day are about 130 ft. long by 30 ft. wide, and hold 1 300 tons of glass.

Manufacture

Glass can be blown, drawn, rolled or moulded, the working temperature being regulated to give the viscosity required by the particular process.

The penetration of the engineer into the industry in the last 30 years has accelerated the replacement of the man by the machine in the manufacture of glass. This change, now almost complete so far as the mass production of glass is concerned, has necessitated a close control of the composition and working temperature of the glass. The highly skilled glass worker instinctively dealt with

variations in the glass in a way which the machine cannot imitate.

(2) STRAIN IN GLASS

When glass cools from a high to a room temperature, internal strains develop and the final magnitudes of these strains depend upon the transient temperature distribution in the glass during the cooling period.

The "Strain Temperature" of a Glass

While the increase of viscosity with decreasing temperature is continuous, it is often convenient in discussing the development of strain in cooling glass to assume that there is a viscosity at which a glass may be regarded as changing from a viscous liquid to an elastic body capable of acquiring strain.

The temperature corresponding to this viscosity is called the "strain temperature" of the glass.

The Development of Strain in Cooling Glass

If a glass slab, at uniform temperature, is exposed to an atmosphere and surroundings at a lower temperature than its own, it loses heat by convection and radiation. During the cooling period, heat flows from the interior to the surfaces, and in a region remote from the edges the flow of heat is perpendicular to the faces of the slab and to the isothermal surfaces, which are planes parallel to those faces.

In Fig. 2, which shows such a region in a slab of thickness d , V is an elementary volume whose faces are isothermal surfaces of equal area through which heat is flowing normally. In unit time the heat flowing out through its face A is greater than the heat flowing in through its face B by the rate at which the elementary volume is losing heat; i.e. by the rate at which its temperature is falling, multiplied by its heat capacity.

As the temperature gradient at surface A or B is directly proportional to the rate of flow of heat through that surface, the temperature gradient at A is greater than that at B and thus at any instant during the cooling period the temperature gradient in this region of the slab is a maximum at its faces and a minimum (zero) at its middle layer.

Fig. 2 also shows some instantaneous temperature distributions taken at intervals during the time the temperature of the middle layer of the region is falling from T_0 to T_s , where T_0 is the initial uniform temperature of the slab and corresponds to a viscosity at which no strain can exist in the glass for any appreciable time; and T_s is the strain temperature of the glass as described above.

In Fig. 2, L is an elementary layer whose faces are planes parallel to the faces of the slab. During the cooling period, the glass in this layer remains viscous and, therefore, unstrained, until its temperature has fallen to the strain temperature of the glass, with the result that at that temperature this elementary layer consists of unstrained elastic glass with a temperature gradient across its faces.

When, however, the temperature of the whole slab has fallen to the lower temperature of its surroundings (T_1) and this temperature gradient has ceased to exist, the

glass in this layer L is in a state of strain because its faces have fallen through slightly different temperature ranges after the glass has become elastic.

The strain gradient across the layer is then proportional to the instantaneous temperature gradient which existed in the layer when at the strain temperature and to the coefficient of expansion of the glass. It follows that the shape of the final strain curve, shown in Fig. 3, can be derived from temperature-distribution curves similar to those in Fig. 2, as each curve shows the temperature gradient in a particular layer of glass as its temperature falls through the strain temperature. This temperature gradient is a maximum at the faces of the slab and a

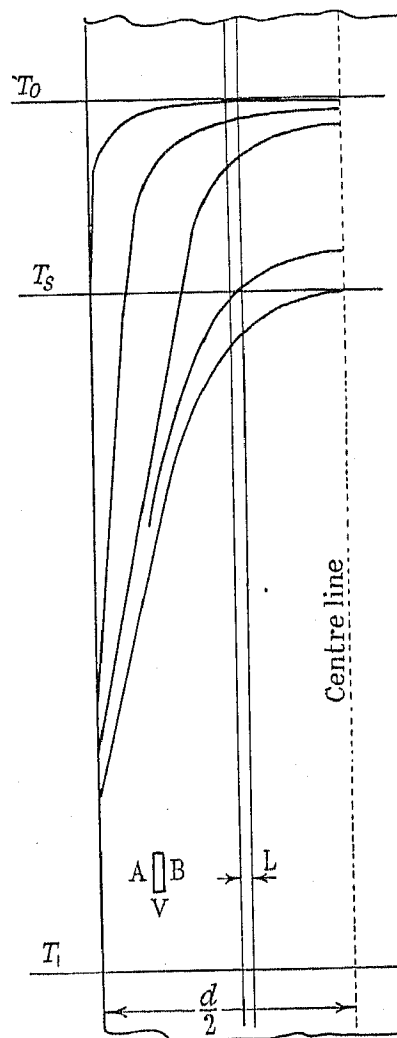


Fig. 2.—Instantaneous temperature distribution in cooling glass.

minimum (zero) at the middle layer, and the resultant strain curve is more or less parabolic.

As the stress in the glass is proportional to the strain a stress curve would be identical in form. This proportionality enables the position of the base line of the strain curve to be determined. The resultant of the forces acting across the section of the glass must be zero, and this condition is satisfied if the area enclosed between the curve and the base line is equally divided above and below that line.

The Measurement of Strain

Strain in transparent glass can be measured by means of polarized light, because the velocity of light in glass (and, therefore, the refractive index) depends on the average distance between the atom groups and this varies with the strain.

The most convenient apparatus for the measurement of strains in glass is the Babinet compensator. This consists of two wedges of quartz, one cut with the optic axis of the crystal along the length of the wedge, and the other with the optic axis perpendicularly across the wedge and parallel to the two inclined wedge surfaces.

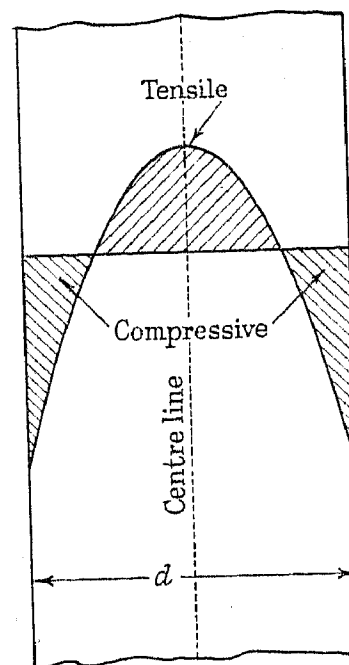


Fig. 3.—Permanent strain distribution in cooled glass.

The wedges are cut to the same angle and are cemented together so as to form a parallel-sided assembly (Fig. 4). The compensator is mounted with the optic axes of the wedges horizontal and vertical respectively, and a parallel beam of monochromatic polarized light is passed through it in a direction normal to the outer vertical faces. If the original direction of vibration of the light is at 45° to the horizontal, the light is resolved by the first wedge into vertical and horizontal sets of vibrations of equal amplitude. The two sets enter in phase, but one travels more rapidly than the other through this wedge.

In passing through the second wedge these vibrations are not affected in amplitude or direction, but their velocities are interchanged. Thus the vibrations passing

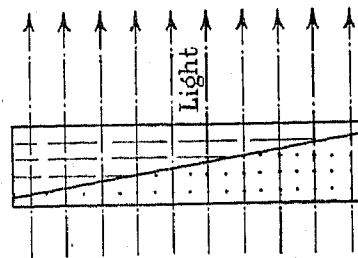


Fig. 4.—Babinet compensator.

through the middle of the wedge system have equal total times of travel and emerge in phase with each other. Their resultant on emergence is thus a beam of plane-polarized light vibrating at 45° to the horizontal, having, on the whole, suffered no change in its state of polarization.

This light, when received by an analyser turned to transmit plane-polarized light vibrating at 135° to the

horizontal, is completely suppressed, and when viewed through this analyser the centre line of the compensator appears dark.

The polarized light passing through any part of the compensator is similarly split up into vertical and horizontal vibrations as it enters the first wedge. Away from the centre line, however, the light travels through different thicknesses of the two wedges, and one of the beams will be retarded relative to the other, the retardations depending on the differences between the thicknesses of the wedges along the paths traversed by the light. On the one side of the centre the horizontal vibrations will lag behind the vertical vibrations, and on the other side they will be in advance.

The lag or lead along some particular path in the compensator will be exactly equal to a whole wavelength of the light, and the equivalent *total* phase difference will be 360° . The conditions in the emerging light will thus be exactly the same as in the light which passes through the centre, and the resultant vibration at 45° to the horizontal will be completely suppressed by the analyser. Similarly, at all points on either side of the centre line where the lag is equal to some multiple of a wavelength the *effective* phase lag will be zero and the emerging light will again be suppressed by the analyser.

Midway between these "extinction" positions the effective phase differences will be equal to 180° , and the resultant vibrations, being at 135° to the horizontal, will be completely transmitted by the analyser. At other points the resultant vibrations will be elliptical in character, with "circular" vibrations where the phase differences are 90° and 270° , and will be partially transmitted. When the compensator is viewed through the analyser, therefore, it will appear to be crossed by vertical dark bands at equal distance from each other (corresponding to zero effective phase change), with spaces showing gradations of brightness between.

A piece of strained glass placed in the beam of light produces a lag or lead which is added to, or subtracted from, the retardation produced by the compensator, causing the dark lines of the compensator pattern to be displaced. The displacement of these lines is proportional to the difference between the vertical and horizontal strains in the glass, and this difference can thus be measured if the compensator has been appropriately calibrated. To calibrate the compensator, a piece of annealed glass of the same composition as that under examination is set up and is subjected to various known bending loads; the tensions and compressions corresponding to these loads can thus be related to the observed displacements of the lines.

The displacement is proportional to the difference between the vertical and horizontal strains in planes normal to the path of the light, multiplied by the thickness of glass traversed by the rays.

With a heavily strained glass it is not easy to recognize any particular line if monochromatic light is used, and there is some difficulty in measuring the displacements; this difficulty can, however, be avoided by the use of white light.

With light of any wavelength the centre band always corresponds to zero lag and zero phase difference and so always appears black. As the spacing of the bands, how-

ever, depends on the wavelength of the light used, the mixture of wavelengths constituting white light gives side-bands fringed with colour, and only the central band appears black. With white light, therefore, the central band can always be recognized and its displacement readily measured.

A convenient optical system for measuring strain in glass by means of the Babinet compensator is shown in Fig. 5. In this system the objective lens throws a focused image of the glass specimen on the Babinet wedges, and the projection lens throws a combined image of the wedges and the specimen on to a screen on which the displacement of the black central line can be measured.

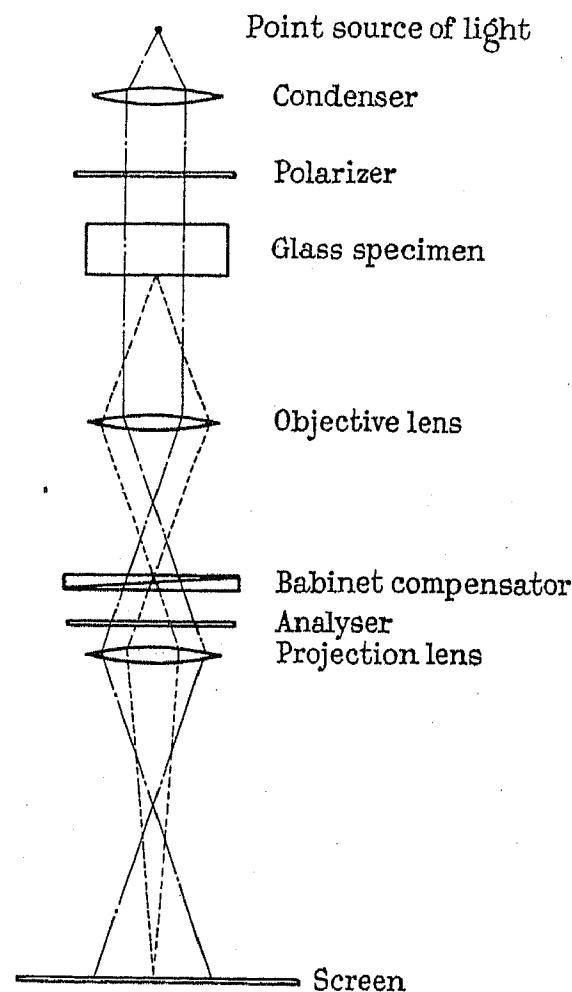


Fig. 5.—Optical system for measuring strain in glass.

Control of Strain

The development of strain in cooling glass and the resultant strain distribution in the cooled glass have been discussed earlier in this paper.

The magnitudes of the permanent strains depend on the rate of cooling, on the coefficient of expansion of the glass, and on the ratio between its thermal conductivity and its specific heat per unit volume. The stress at any point is proportional to the corresponding strain, the ratio between the two depending upon the elastic constants of the glass.

Thus for any given glass the permanent stresses can be controlled by the rate of cooling, which is so adjusted that the desired results are obtained.

In practice two cases arise, (i) annealed glass, and (ii) pre-stressed or toughened glass, and a comparison between the two is interesting.

(i) Annealed Glass.

The strains produced by the rapid and uneven cooling to which glass is subjected during manufacture are almost entirely removed during annealing.

The annealing process consists of maintaining the glass at a temperature at which any existing strains disappear in a reasonable time and then cooling it slowly enough to prevent the introduction of more than a permissible amount of strain. This process is usually carried out by passing the glass through a tunnel, or "lehr," along which a suitable temperature gradient is maintained. The time taken to anneal glass in this way depends largely on its thickness and size, and for commercial glassware it varies between 3 hours and 24 hours.

When the quantity produced does not warrant continuous annealing, the glassware is placed in a heated kiln which, when full, is allowed to cool slowly. In commercial annealing the glass is usually left with a slight permanent compressive strain in the surface layers, as this increases the resistance to mechanical and thermal shock.

(ii) Pre-stressed or Toughened Glass.

Pre-stressed or toughened glass is glass which has been so treated after manufacture as to produce intentionally a strain distribution in which the surface layers are in a state of high compression.

The process of pre-stressing or toughening glass consists of heating the glass to a uniform temperature considerably above its strain temperature and then cooling it rapidly, usually by blowing air on all its surfaces, under carefully controlled conditions. The resulting strain distribution, which is similar to that shown in Fig. 3, greatly increases the resistance to mechanical and thermal shock.

From Fig. 3 it will be seen that the interior of toughened glass is in a state of tension and the rate of cooling must be so adjusted that the maximum tension in the central layer does not exceed a safe value.

The process is limited to comparatively simple shapes in which a satisfactory strain distribution can be obtained.

Comparison between Annealed and Toughened Glass

If a piece of annealed glass is toughened its resistance to mechanical loads and thermal shocks is greatly increased, although the composition of the glass is unchanged. The increased resistance to mechanical loads can best be understood by considering the resistance to bending. If a strip of annealed glass is supported at each end and gradually loaded at the centre until the glass breaks, the fracture almost invariably begins at the lower surface where the tension is a maximum.

The breaking load may be regarded as a measure of the weakness of the surface rather than of the strength of the glass. The true, or "interior," tensile breaking strain of the glass is much higher than its average "surface" breaking strain, which depends on the state of the surface.

If a similar experiment is carried out with a strip of toughened glass in which all the surfaces are initially in compression, the load can be increased until the compression in the lower surface is converted into the tension at which the glass breaks. In this bending test the load required to break a strip of highly toughened glass is

between four and five times that which breaks a similar strip of annealed glass of the same composition.

The increased resistance of toughened glass to thermal shock is also due to the initial compression in the surface layers.

When hot glass is suddenly plunged into water at a lower temperature, the immediate contraction of the surface layers is resisted by the interior which has not had time to cool appreciably, and in this way a sufficiently large and sudden temperature change will produce the breaking tension in the surface layers. In the case of toughened glass, however, the temperature "shock" required to cause fracture is much greater than that which will break annealed glass, owing to the initial high compression in the surface layers of the toughened glass.

(3) PRE-STRESSED ("TOUGHENED") GLASS INSULATORS**(a) Manufacture****General.**

The electrical and mechanical properties of toughened glass immediately suggest its application to the manufacture of insulators.

The uniformity of the raw material can be ensured by the continuous production of homogeneous glass of constant chemical composition.

The electric strength of glass is so high that there is no difficulty in designing an insulator which cannot be punctured in air by voltage surges.

The surfaces of toughened glass are initially in a state of compression and, by virtue of this initial compression, a glass insulator easily capable of withstanding the maximum mechanical and thermal stresses normally encountered in service can be produced.

Long life can be anticipated, because under service conditions no surface crack can develop in the compressed surface layers; it is now generally recognized that the so-called "ageing" of insulators in the past was merely the slow development of these cracks.

As mechanical breakage, or electrical puncture, results in the complete shattering of toughened glass, any toughened-glass insulator which is visibly whole must be mechanically and electrically sound, and the locating of a faulty insulator from the ground or from the air is a very simple matter. This shattering is due to the release of the potential energy stored in the strained glass.

Choice of Glass.

The choice of a suitable glass can be made with almost sole reference to "weathering" qualities, as no compromise need be made so far as electric strength and ability to withstand mechanical and thermal shocks are concerned.

The great resistance of toughened glass to thermal shock enables a glass with a relatively high coefficient of expansion to be used, and this has the advantage that the coefficient of expansion of the glass can be more nearly equal to that of any fitted metal cap or pin. The chosen glass is of the lime-soda family and has a coefficient of linear expansion of 8.7×10^{-6} per degree Centigrade.

Pressing.

The power-line insulators under consideration are composed of one-piece glass pressings, or, in the case of the larger pin-type units, are made as a number of separate pressings which are afterwards cemented together to form the complete insulator.

The glass pieces required for a range of pin-type and cap-and-pin disc-type insulators are among the comparatively simple shapes which can be successfully pressed and toughened.

The pressing of the glass pieces is essentially a simple operation but calls for skill and care. A quantity of molten glass, at a temperature of about 1 000° C., is gathered in an iron ladle from the working end of the tank furnace and poured into a crucible cast-iron mould with chill-hardened working surfaces. A plunger of the same material is then brought down and the glass pressed into the required shape.

When the outer surfaces of the glass have set and the piece is sufficiently rigid to be handled, the plunger is raised, the mould opened, and the glass placed in an "equalizing" furnace at a temperature of about 700° C.

This furnace is of the revolving-hearth electrically-heated type with resistance elements in the hearth and in horizontal recesses in the outer wall of the heated annular space.

Thermostatic control is used to ensure constant temperature.

Toughening.

The hearth of the equalizing furnace rotates at a constant speed which is preset to ensure that each glass pressing remains in the furnace sufficiently long to equalize the temperatures throughout the piece.

The glass piece is then taken out of the furnace and rapidly cooled by means of compressed air.

The rate of cooling is adjusted to give a safe maximum tension in the central layer of the glass, and uniformity of product is attained by close control of time and temperature at each stage of the process.

The development of strain in cooling glass has been dealt with at some length earlier in the paper, and need not be repeated here.

Routine Thermal Shock Test.

The cold toughened-glass pieces are then subjected to a thermal shock test by suddenly pushing them into a kiln at a temperature of 550° C. and allowing them to remain there until the transient temperature gradient in the glass has passed through its maximum.

The object of this test is temporarily to increase the tension in the central layer by the thermal expansion of the surface layers, and thus weed out any defective piece.

Partial De-toughening.

After the glasses have been proved by the thermal shock test, they are partially de-toughened by exposing them to a temperature of 450° C. for the required length of time. This increases the factor of safety by slightly lowering the maximum tension in the central layer, and completes the toughening process. In the finished insulator this tension is in the order of 8 000 lb. per sq. in.

Inspection.

The glass pieces are then examined and gauged by inspectors. In this examination the transparency of the material is very valuable, as any internal fault is easily seen and any defective piece rejected before it reaches the assembly plant.

Assembly.

The assembly need not be described in detail. The component parts, metal and glass, are joined together by an aluminous cement without the use of any resilient medium. Every operation is jugged to ensure correct alignment of the parts.

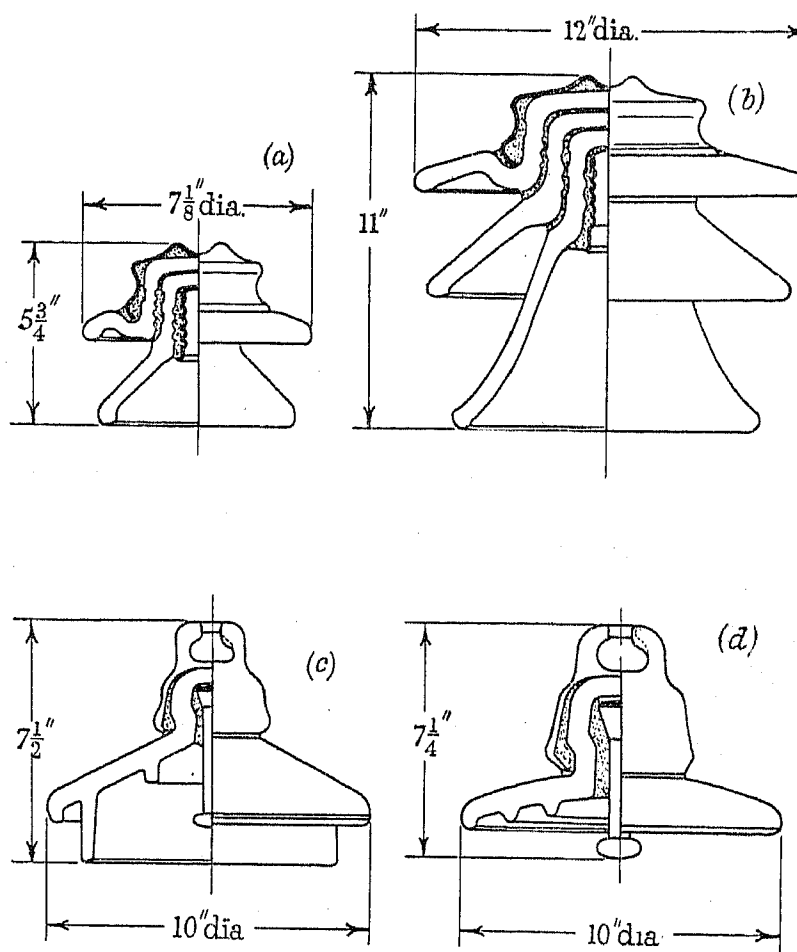


Fig. 6

- (a) 11-kV pin-type insulator.
- (b) 33-kV pin-type insulator.
- (c) Anti-fog suspension-type insulator (10 000 lb.).
- (d) Heavy-duty tension-type insulator (28 000 lb.).

The pin-type insulators are fitted with copper or aluminium caps and screwed copper ferrules. The metal cap enables the insulator to support the line mechanically should the top shed be broken, and also raises the voltage at which radio interference starts.

Types.

Typical toughened-glass pin-type and disc insulators are shown in Fig. 6.

(b) Development Tests

During the development period many preliminary and long-duration tests were made in order to ensure the satisfactory performance of the insulator in service.

Some of the long-duration tests are still in progress, and these tests will be continued until they have served their purpose.

Toughening Tests.

Most insulator pieces are of such a shape that direct measurements of the stress in the glass by means of the Babinet compensator is impossible. This instrument can, however, be used to measure the stress in simpler shapes such as a plate, or cylinder, and the results used as a guide in the toughening of more complicated glass pieces.

The size of the fragments of a shattered insulator piece is some measure of the degree of toughening, and samples taken continuously from manufacture are broken and compared with standards which have been established by experience.

While reference to this scale has given good results in practice, it is hoped eventually to obtain sufficient data to enable the toughening process to be controlled by means of the routine use of the Babinet compensator.

With this in view, readings are taken of the sample pieces in this instrument and the results related with the fragmentation when the pieces are subsequently broken.

Experience suggests that within the range met with in manufacture it may be possible to rely entirely on these readings as a measure of uniformity.

Cement Tests.

After many preliminary tests an aluminous cement was finally adopted. This cement has a high mechanical strength and does not adhere to the glass. This choice has been justified by experience.

A further investigation of cements is now in progress. The annular space between two concentric cylinders of strain-free glass is filled with the cement to be tested and the assembly placed in the open, or exposed to controlled temperature and humidity conditions.

Any stress in each of the two cylinders is measured at intervals by means of the Babinet compensator. It is hoped that this test will eventually give valuable information regarding the behaviour of cements over a long period of time.

Mechanical Tests.

(i) *Disc Insulators*.—The strength of a toughened-glass disc appeared to solve the mechanical problems met with in the design of the tension insulator, and as a preliminary step a 10-in. diameter disc insulator having an ultimate tensile strength of 15 000 lb. was produced.

When this insulator was tested to destruction the metal fittings failed between 18 000 lb. and 20 000 lb., but in no case was the glass disc broken.

In an attempt to ascertain the ultimate strength of the glass disc, a strengthened cap and high-tensile steel pin were then fitted. This enabled loads up to 30 000 lb. to be applied before the pin failed, but again no glass disc was broken.

A long-duration test was started in May, 1935, when a string of these glass discs was assembled with normal fittings and erected in the open under a constant load of 10 000 lb. The pins are still slowly elongating, but after $4\frac{1}{2}$ years under this load all the glass discs are intact.

Subsequently, strings of 10 000-lb. and 28 000-lb. insulators, with designs based on the experience gained with the 15 000-lb. unit, were placed in the open under

loads of 10 000 lb. (in July, 1939) and 20 000 lb. (in March, 1939) respectively.

It is too soon to regard these tests as of long duration, but it may be said that up to date no failures have occurred.

Another long-duration test has recently been started in which strings of 10 000-lb. disc insulators are loaded to 4 000 lb. and the conductor is maintained in a state of continuous vibration. Some considerable time, however, must elapse before the results of this test can have much value.

When toughened glass breaks it shatters completely, and tests were therefore made to determine the mechanical strengths of shattered tension insulators. In one test, a 10-in. diameter insulator was loaded to 10 000 lb. and the glass disc deliberately broken.

This load was sustained for 5 minutes and then slowly increased until the pin failed between 18 000 lb. and 20 000 lb. The test was then repeated with the insulator under vibration, with the same result.

A similar test was made on the 10-in. diameter 28 000-lb. disc insulator. In this test the insulator was loaded to 12 000 lb. before the glass disc was deliberately broken and, when the load was slowly increased, failure occurred at 28 500 lb., owing to the cap and pin pulling through the broken glass.

Although these tension insulators were designed to hold the conductor in the event of the glass disc being broken, these results are surprisingly good.

(ii) *Pin Insulators*.—In the case of pin insulators, tests were made to ensure that the specified loads could be withstood without damage to the insulator or appreciable permanent set in the spindle.

Samples of the 11-kV and 33-kV insulators, with a transverse load of 2 000 lb. applied to the side groove of the metal cap, were placed in the open in September, 1937. Since that time periodic inspections have shown that no relative movement of the insulator parts has taken place, although the spindles have slowly bent.

As the copper, or aluminium, caps are fitted on the pin insulators in order to support the line mechanically should the top shed of the insulator be broken, these tests were repeated after the top shed had been deliberately shattered. In every case the spindle was bent before the cap pulled off, at loads up to 4 500 lb.

Electro-mechanical Tests.

As the result of an investigation which showed that, if a toughened-glass piece is intact mechanically, it is also sound electrically, all electro-mechanical development tests were abandoned. Subsequent experience gained in routine has justified this decision, and no disc-type or pin-type toughened-glass insulator has ever failed on the routine "high-voltage" test. There is no technical reason why this routine test should not be omitted so far as toughened-glass insulators are concerned.

Puncture Tests.

(i) *On New Insulators*.—The results of power-frequency puncture tests on disc insulators completely immersed in "standard" insulating oil (B.S.S. No. 148—1933) were very unsatisfactory. The puncture voltage was sometimes as low as 80 kV, and in every case the insulator was

punctured not through the head but through the glass skirt, usually $\frac{1}{2}$ in. to 1 in. beyond the edge of the cap.

An emulsion of standard insulating oil and a small quantity of water gave rather better results, but puncture often occurred at abnormally low voltages and still invariably through the skirt of the insulator.

The use of a lignite tar oil with the addition of 5 per cent cable-box compound* raised the minimum puncture voltage to 170 kV, but again the puncture was always through the glass skirt and not through the head of the insulator. This compound-treated oil did, however, enable 200 kV (the highest available voltage) to be applied without puncture occurring in over 80 per cent of the tests on disc insulators.

The results of puncture tests made on pin-type insulators under standard oil were better, but in the larger sizes puncture sometimes occurred through the skirts. Since the adoption of the compound-treated oil no pin-type insulator has been punctured at 200 kV.

The addition of the compound greatly increases the conductivity of the lignite tar oil, but the proportion which should be added does not appear to be critical as the addition of $2\frac{1}{2}$ per cent (instead of 5 per cent) of compound gives equally good results.

(ii) *On Disc Insulators, after Long-Duration Mechanical Overload Test.*—In order to ascertain whether mechanically overloaded glass disc insulators deteriorate electrically with time, eight 10-in. dia., 15 000-lb. units were taken from a string which had been in the open for $4\frac{1}{2}$ years under a load of 10 000 lb. and tested under lignite tar oil to which $2\frac{1}{2}$ per cent of cable compound had been added. Seven of the eight insulators remained unpunctured at 200 kV (the highest available voltage), while one punctured through the skirt at 185 kV.

The result of this test confirmed that the compressed surface layer had succeeded in preventing the development of any incipient surface crack.

(iii) *On Disc Insulators after a Long-Duration Temperature-Cycle Test.*—A similar puncture test under the compound-treated oil was made on four 10-in. dia., 15 000-lb. units taken from a string which had been loaded to 7 500 lb. in a thermal-cycle chamber for $2\frac{1}{2}$ years.

During this long-duration test the insulators had been subjected to over 4 800 cycles, consisting of 2 hours' heating in steam to 75° C. (167° F.) followed by 2 hours' cooling in artificial rain falling at the rate of 24 in. per hour. The temperature of the water varied with the season of the year, the average temperature being about 11° C. (52° F.).

The four insulators remained unpunctured at 200 kV.

Details of this long-duration temperature-cycle test are given below under "Temperature-Cycle Tests."

Maximum Impulse Sparkover Tests.

Maximum impulse sparkover tests were carried out on strings of 7-in. and 10-in. dia. disc insulators and on all sizes of pin-type insulators.

The impulse generator was set to give a peak voltage which ensured sparkover on the wave front, which was of 1 microsec. or less.

All the insulators were subjected to 500 impulses at

the maximum impulse sparkover voltage, and in every case they withstood the test satisfactorily.

Temperature-Cycle Tests.

After preliminary tests had shown that the usually specified temperature-cycle tests with temperature changes up to 100 deg. C. could be easily met, it was decided to start a long-duration test in which the worst service conditions could be reproduced. These conditions are probably met with in the tropics, where an insulator may be repeatedly heated by fierce sunshine and then cooled by torrential rain falling vertically.

For this test a lead-lined wooden chamber 6 ft. $\times$ 6 ft. 6 in. $\times$ 7 ft. 6 in. high was constructed. In this chamber perforated steam pipes are fitted at floor-level and rain spray nozzles arranged in the roof. The insulators are supported on a trestle at 21 in. above floor-level.

The steam supply is controlled by a magnetically

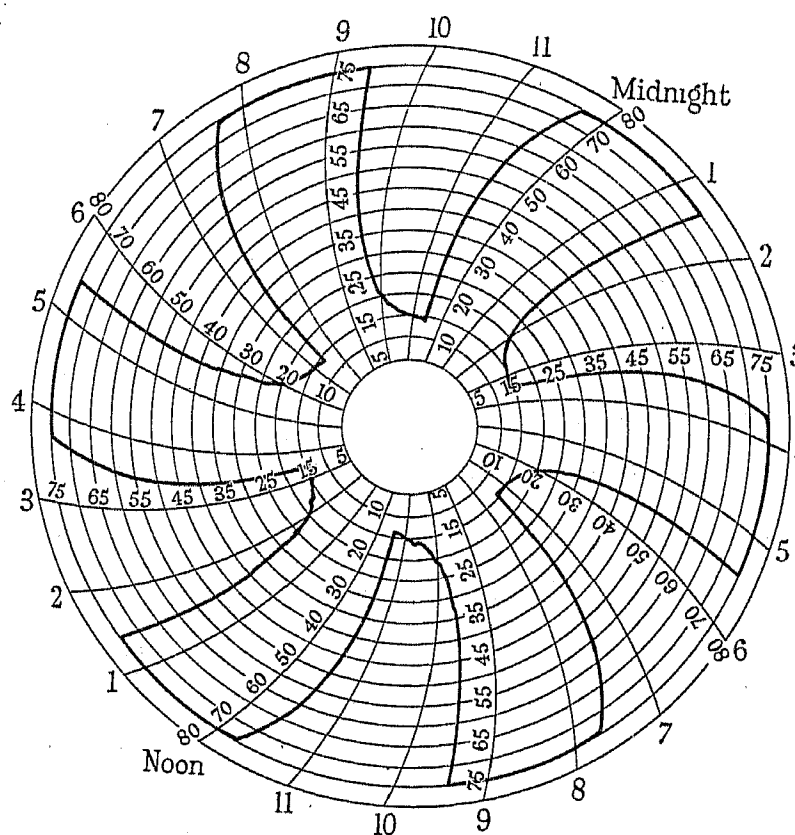


Fig. 7.—Atmospheric temperature in temperature-cycle chamber.

operated valve, controlled in turn by a thermostat which can be set to maintain the desired maximum temperature (75° C.). The water supply valve is adjusted to give the desired rate of rainfall (24 in. per hour), and the heating and cooling periods (2 hours each) are controlled by a time switch.

Since the start of this test in October, 1935, over 7 800 cycles, as shown in Fig. 7, have been recorded.

In order to investigate the temperature distribution through the head of a multi-piece pin-type insulator during the cooling period, a 4-piece 33-kV insulator, with thermocouples assembled in all the joints, was placed in the chamber and the temperatures were recorded over a complete cycle.

The results are shown in Fig. 8, from which it will be seen that after 16 minutes' cooling the temperature drop across the top shed rises to a maximum of 32 deg. C. This large temperature-drop is due to the fact that the

* R. VAN CAUWENBERGHE: "Electro-mechanical and Thermal-stresses in Insulators," *Revue Générale de l'Électricité*, 1938, 44, p. 633.

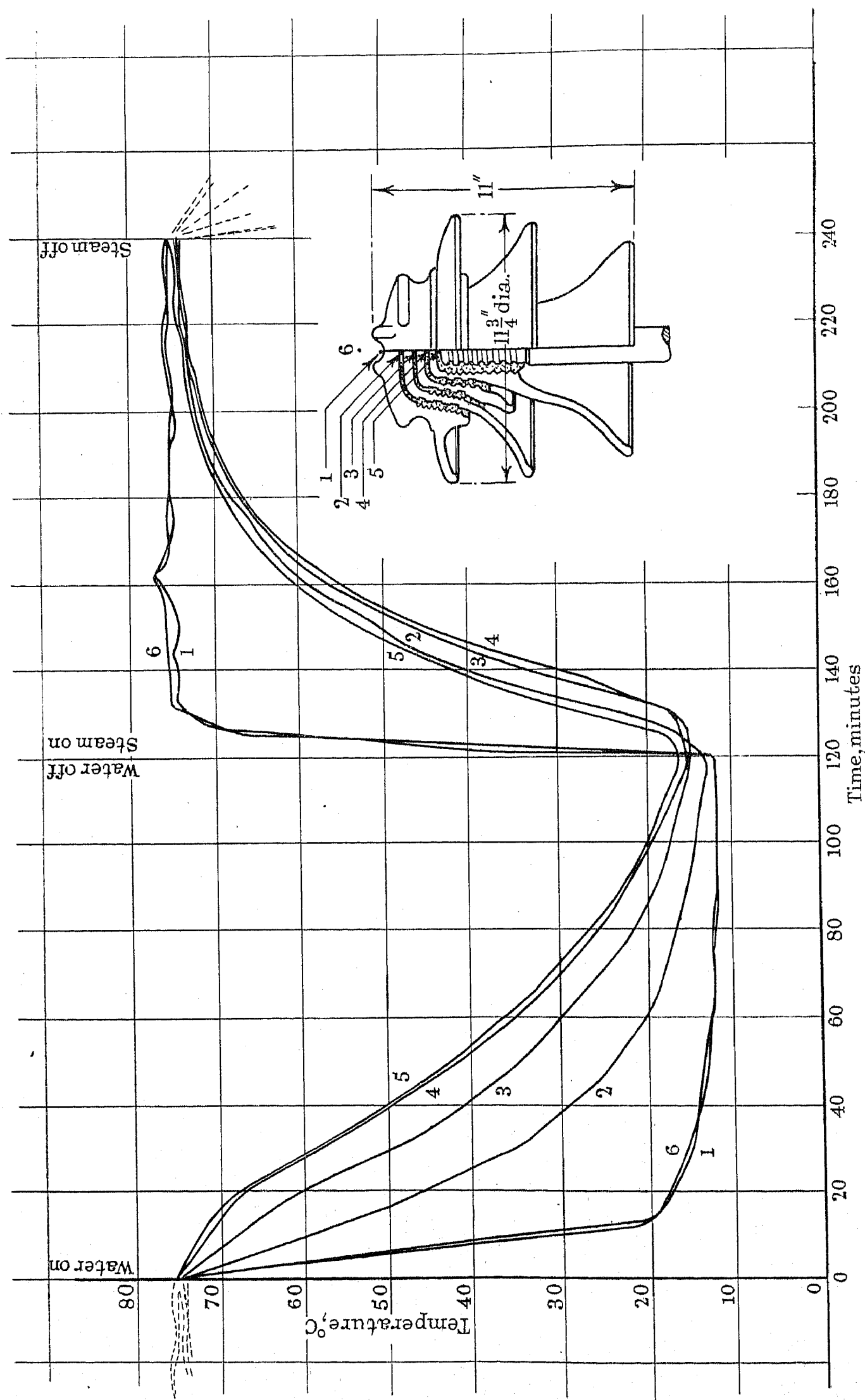


Fig. 8.—Temperature distribution through head of multi-piece pin-type glass insulator.

top shed acts as an umbrella and prevents the vertical rain falling on the lower sheds.

This test confirms the view that during the very heavy rain which usually follows a thunderstorm in the tropics, the temperature distribution through the head of a multi-piece pin-type insulator is such that considerable tension exists in the more rapidly cooled top shed.

Samples of this early (and now obsolete) type of insulator are still intact after being subjected to over 7 800 cycles, while samples of the more recently developed metal-capped pin insulators are still in good condition after from 3 100 to 4 400 cycles.

Sample 10-in. dia. and 7-in. dia. disc insulators are still intact after 7 800 cycles, including, in the case of the 10-in. dia. insulators, 4 800 cycles under a load of 7 500 lb.

This may be regarded as a very severe test and as equivalent to many years' service under the worst tropical conditions.

The ability of the insulator to survive this test is undoubtedly due to the initial compression in the surface layers of the glass, which is the unique feature of the toughened-glass insulator.

Another long-duration temperature-cycle test was started in November, 1937. In this test the insulators are immersed in water at room temperature for 6 hours and then placed in a refrigerating chamber for 6 hours, during which time the temperature of the atmosphere falls to -20°C .

The pin-type and disc insulators are still intact after 1 400 cycles, including, in the case of the 10-in. dia. disc insulators, over 1 300 cycles under a load of 7 500 lb.

Further Tests.

- (1) Effect of power arcs.
- (2) Heating by solar radiation.
- (3) Impact resistance.
- (4) Impulse electric strength of glass.
- (5) Performance in humid and polluted atmospheres.

During the development period, a series of investigations of the properties of toughened-glass insulators was carried out by the British Electrical and Allied Industries Research Association.

A very interesting account of the many tests made by this Association is given in a report entitled "The Performance of Glass Insulators, and Comparisons with Porcelain" (see page 625).

Results in Service

There are now thousands of toughened-glass insulators in service, including some under very severe climatic conditions. Pin-type and disc-type insulators are in use on lines with working voltages up to 33 kV and 132 kV respectively.

The life of the toughened-glass insulator in service is, of course, still unknown, but the results of the long-duration tests give no indication of a limit.

(4) ACKNOWLEDGMENTS

In conclusion, the author wishes to thank the directors of Messrs. Pilkington Brothers, Ltd., for their permission to present this paper, and to acknowledge, with pleasure, the help he has received from his colleagues in its preparation.

[The discussion on this paper will be found on page 656.]

THE PERFORMANCE OF GLASS INSULATORS, AND COMPARISONS WITH PORCELAIN*

[Paper first received 24th November, 1939, and in revised form 16th January, 1940; read before the TRANSMISSION SECTION 10th April, and before the MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 18th March, 1940.]

SUMMARY

The present paper summarizes a number of separate investigations which, owing to their diverse nature, are described in self-contained sections. Nevertheless, they are complementary in that they serve to show the reaction of insulators to various hazards as represented by controlled test conditions and, in particular, indicate the relative behaviour of porcelain and glass insulators.

Part 1 deals with the effect of power arcs which may develop as a result of a flashover, and is confined to suspension insulators. Part 2 indicates the differential heating which may occur under the sun's radiation and which in turn leads to mechanical stresses and the possibility of fracture. Part 3 examines the hazards from stone-throwing and determines the impact resistance of insulators from this point of view. Part 4 provides impulse electric strengths of porcelain and glass from which the possibility of puncture due to surges can be estimated. Lastly, Part 5 notes some service experience on the behaviour of glass insulators in humid and polluted atmospheres. In general, the paper aims to estimate the security of insulators with respect to conditions of service which are not directly related to the standard tests.

The various sections of the paper were contributed by the following organizations and individuals, to whom the Electrical Research Association wishes to make due acknowledgment:—

The work on power arcs was carried out at the E.R.A. Laboratory by Messrs. A. E. Helden and C. E. R. Bruce. The work on the effect of radiation and impact tests was carried out at the E.R.A. Laboratory by Mr. A. M. Thomas, Miss M. V. Griffith and Dr. S. Whitehead. The impulse electric-strength tests were carried out at the High-Voltage Laboratory of the N.P.L. by Messrs. A. H. Davis and W. G. Standring. The observations on exposure to humid and polluted atmospheres were communicated by Mr. J. S. Forrest from the Central Electricity Board.

CONTENTS

Part 1. The Effect of Alternating-Current Power Arcs on Glass and Porcelain Insulators.

- (1) Introduction.
- (2) Method of test.
- (3) Test results.
 - (a) Arc voltage and energy.
 - (b) Variation in repeat tests.
 - (c) Position and cause of insulator fracture.
 - (d) Effect of controlling the arc on the rupture of porcelain insulators.
 - (e) Conditions of rupture of porcelain insulators.
 - (f) Rupture of toughened-glass insulators.
 - (g) Relative effects of arc current and arc duration.

* Official communication (Report Ref. U/T16) from the British Electrical and Allied Industries Research Association.

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PART 1

THE EFFECT OF ALTERNATING-CURRENT POWER ARCS ON GLASS AND PORCELAIN INSULATORS

(1) Introduction

The main object was the investigation of the arc-resisting properties of types of glass insulators recently developed, and in particular to obtain a comparison with similar properties of porcelain insulators. Apart from their comparative value, the tests on porcelain insulators are of interest, as no tests of this particular type have been made previously, since an attempt was made to subject an individual insulator unit to a power arc so as to give the maximum degree of contact with the arc likely to occur in practice, in as controlled and reproducible a way as possible.

Earlier investigations had shown that the striking of an arc over an insulator is a notably erratic phenomenon.† In the initial tests this variability was clearly demonstrated by ciné-camera and arc-voltage records, as well as by visual observation and markings on the insulator surface. The first requirement was thus the setting-up of standard conditions which would render the test a

† See, for example, the photographs of arcs on insulator strings given by ACKERMANN, *Engineering Journal*, May, 1928, 11, p. 309, and BARRERE, C.I.G.R.E., Paris, 1929, Paper No. 89.

THE PERFORMANCE OF GLASS INSULATORS, AND

more uniform and reproducible one, and at the same time increase its severity.

Currents of from 250 amperes to 5 000 amperes were

having 10-in. discs and are shown diagrammatically in Fig. 1. They comprised three makes of porcelain, one each of toughened glass and pyrex. As will be seen, they were all of practically the same size and shape.

(2) Method of Test

The test circuit is shown in Fig. 2, the heavy-current connections being shown as thick lines.

The arc was started in each case by connecting the insulator cap to the pin by a piece of 0.004-in. diameter bare copper wire, stretched over the insulator surface, in the direction which the arc would tend to take as a result of the field produced at the insulator by the current leads. This fused in under 10^{-3} sec., so that little variation could have been caused by variation in conditions at the start of arcing.

At first no effort was made to control the arc's movement. The great variation in length and position of such an uncontrolled arc was at once evident from visual observation and ciné-camera records, while Fig. 3 shows the widespread burns on a porcelain insulator after subjection to one 250-ampere and one 500-ampere arc, each for 1 sec., and Fig. 4 shows the burns on the cap of Unit 11 to which a 1 000-ampere uncontrolled arc had been applied for 1 sec. Fig. 5 [(a) and (b)] also indicates the wide variation experienced in the maximum arc voltage with such an arc.

Thereafter the cap and pin were covered with insulation except in the neighbourhood of the ends of the copper fuse-wire, in order to fix the position of the arc roots on the two electrodes and prevent the arc from circling freely round the insulator. Initially the cap was wrapped with asbestos tape, but latterly a quartz cylinder was placed over it with a small notch in its lower edge for the arc, while plastic insulation was used on the pin throughout. This method is referred to where necessary as "electrode control."

Fig. 6 shows photographs of an insulator (Unit 2) which had been subjected to a 500-ampere arc for 1 sec.,

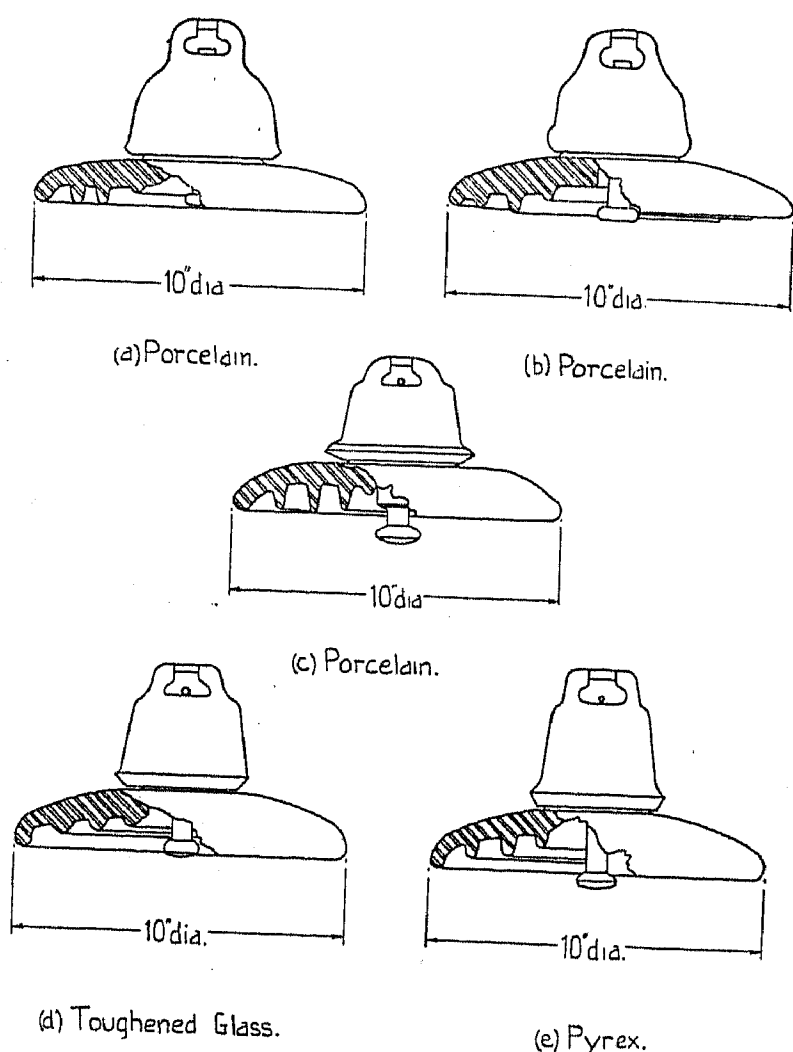


Fig. 1.—Types of insulator included in the tests.

employed, the duration being restricted in the latter case to 0.5 second, while for arcs of 1 000 amperes it lay between 1 and 2.5 seconds.

The insulators tested were all of the suspension type

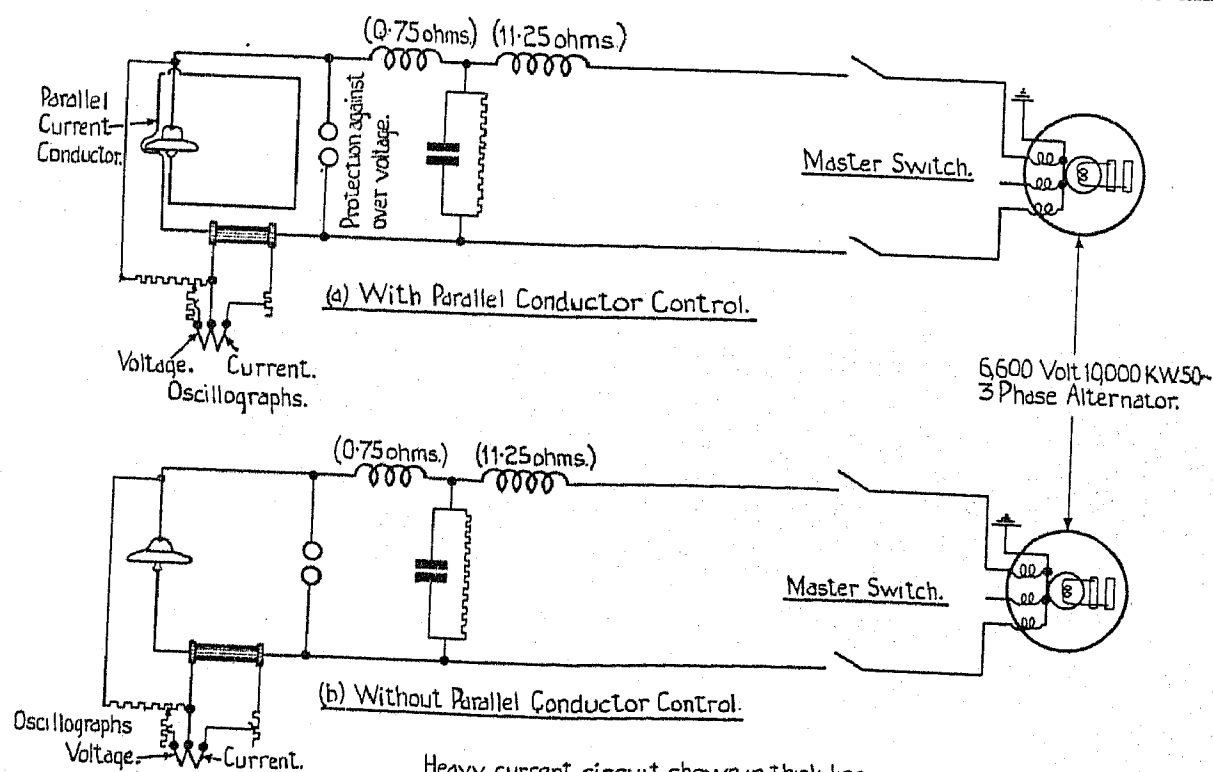


Fig. 2.—Diagram of connections.

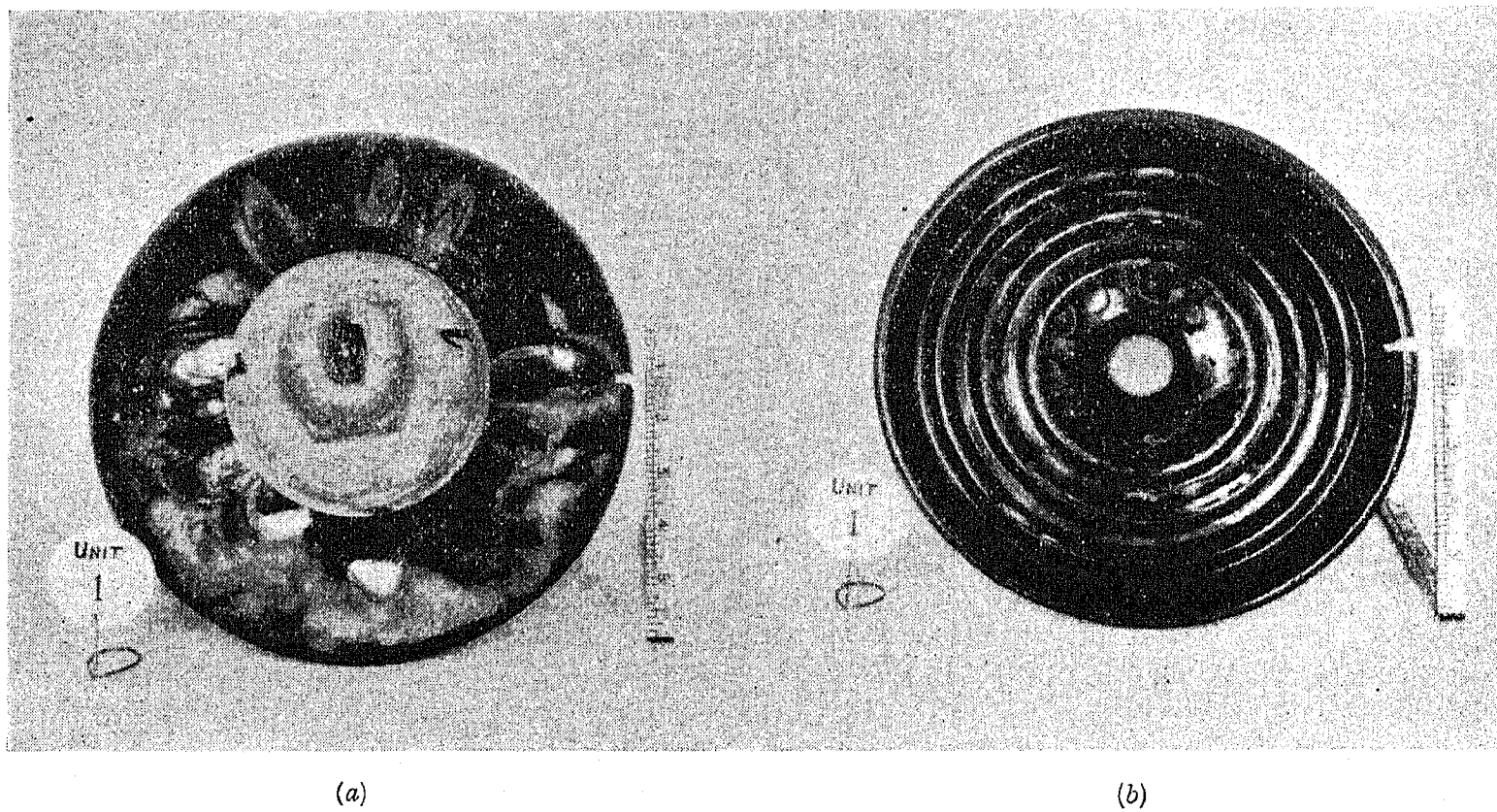


Fig. 3.—Unit 1 after the application of uncontrolled arcs of (a) 250 and (b) 500 amperes each for 1 sec.

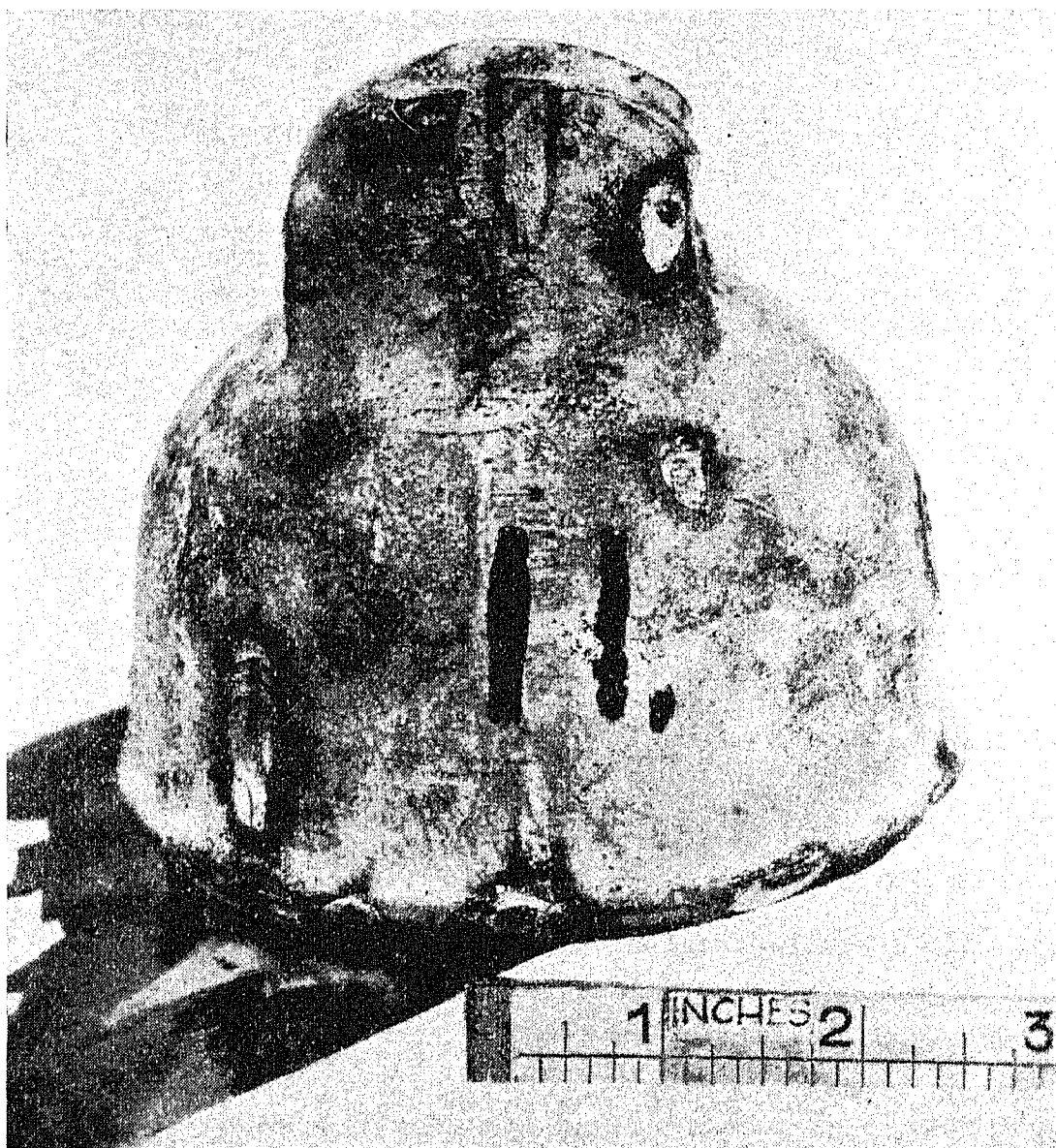


Fig. 4.—Unit 11 after one application of uncontrolled 1 000-ampere arc for 1 sec., illustrating movement of arc root over cap.

in which case revolution of the arc around the disc had been prevented by electrode control.

Fig. 7, however, shows that considerable movement of the arc was still possible and this is borne out by the

Fig. 8. This control by means of the parallel current element in addition to the insulation on cap and pin is referred to as "complete control." Visual observation indicated that the arc remained fixed in position when

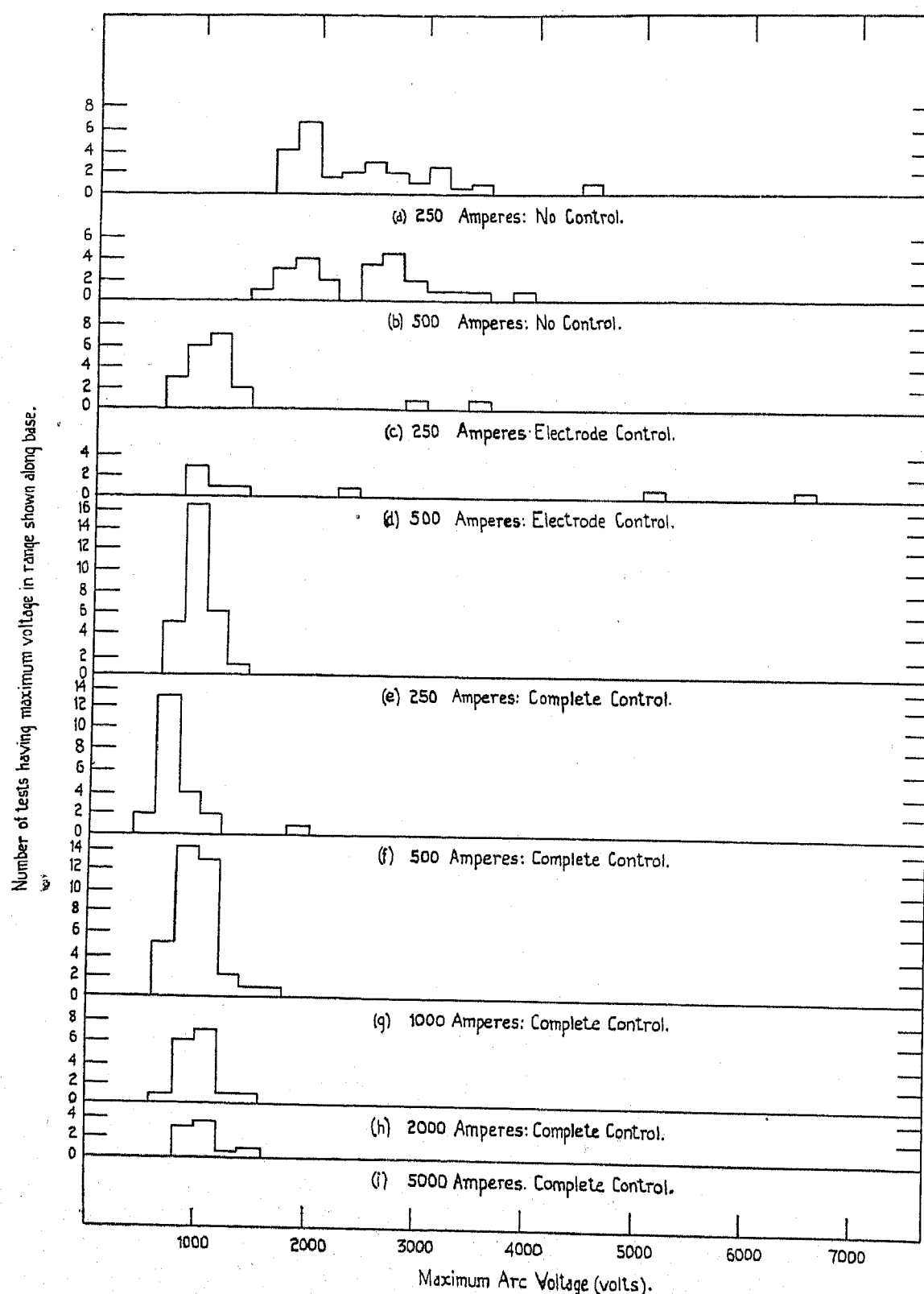


Fig. 5.—Values of maximum arc voltage observed in tests with different currents and methods of arc control. (Note: A wide range of maximum arc voltage indicates great variation in length of arc.)

variation in the maximum arc voltage shown in Fig. 5 [(c) and (d)]. A more successful attempt at its control was made by striking the arc close to an insulated parallel conductor, which was shaped to lie as closely as possible around the insulator and carried the circuit current so that the arc was attracted by this parallel current.* This arrangement is indicated diagrammatically in

"completely controlled." This was borne out by the ciné-camera records, of which Fig. 9 is a typical enlargement. Diagrams (e) to (j) of Fig. 5, when compared with (a) to (d), show in a striking way the reduction in variability of the phenomena when this method of arc control is applied.

In later tests a clock face behind the insulator enabled events on the ciné-camera record to be correlated with the current and voltage record, since a contact maker, rotating with the "clock" hand, made and broke a

* In some tests this conductor was divided into two or three parallel paths, but this did not appear to improve the extent of the control exerted on the arc.

circuit as it passed each "hour" position, so that an oscillographic record of its travel was obtained as well as a visual record. This correlation of the two records is illustrated in Figs. 10 and 11, in which corresponding

(3) Test Results

Over 200 tests were made on 110 units, and the data are summarized in Tables 1 and 2 for porcelain and glass insulators respectively. The tests are grouped first

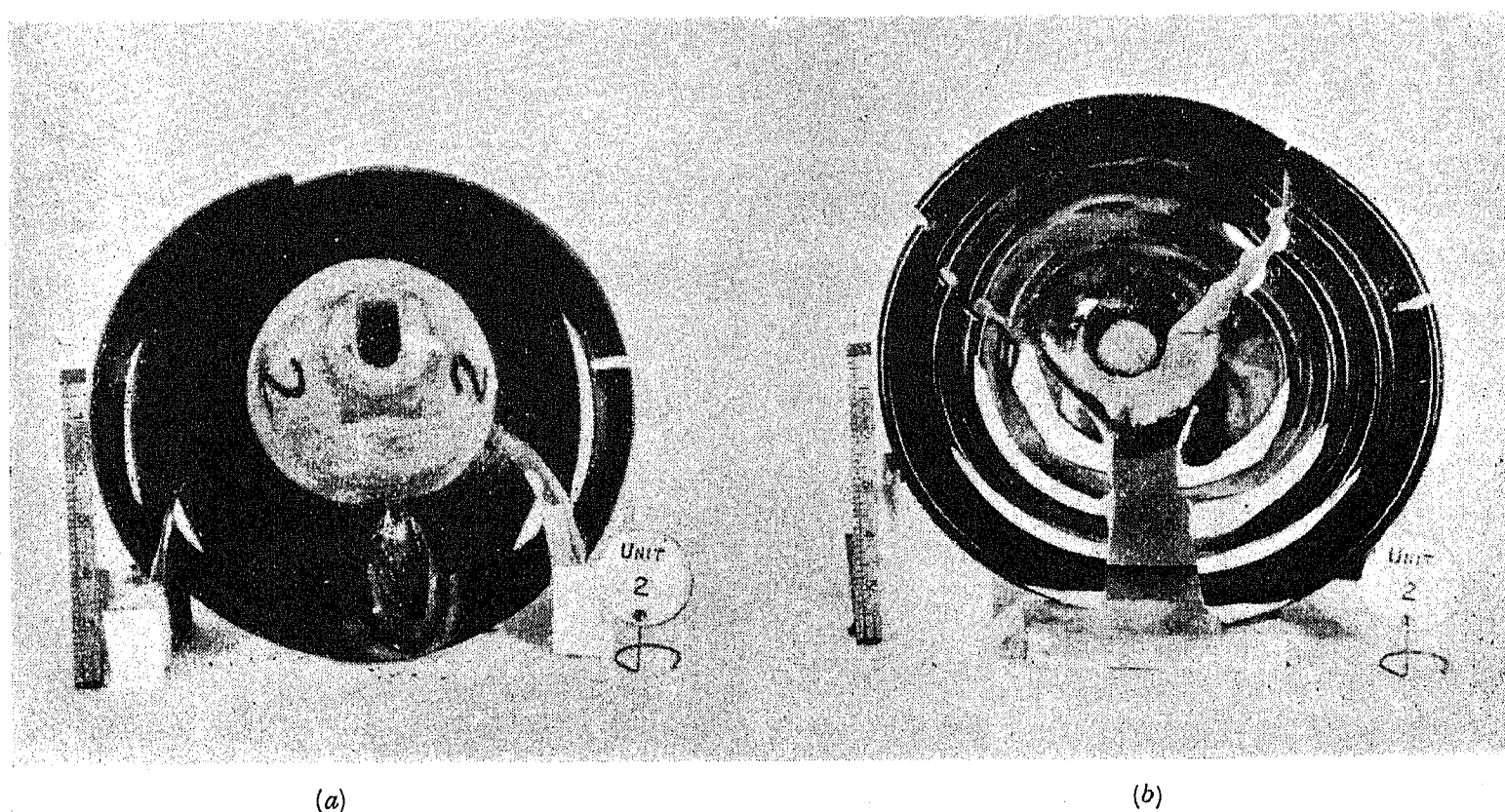


Fig. 6.—Unit 2 after the application of a 500-ampere arc with "electrode" control for 1 sec.

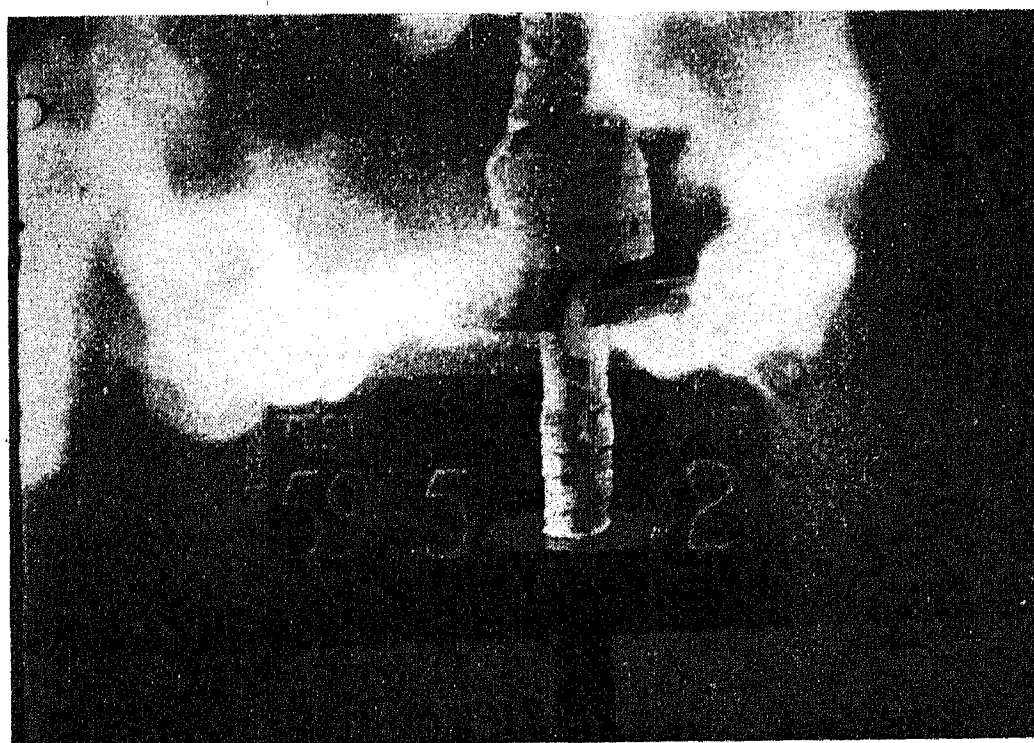


Fig. 7.—Ciné enlargement of 500-ampere arc with electrode control only.

portions of the two records for Test 6045 have been reproduced. Between the successive ciné pictures of Fig. 10 the arc has disappeared from the top of the insulator entirely, only the glowing edges of the silica shield being visible. The arc had burned through the insulation on the parallel conductor, and the resulting drop in the arc voltage due to the shortening of the arc is easily visible in Fig. 11.

as to type or make of insulator, and these groups are in turn sub-divided according to the current in the arc and its duration and the nature of the control of the arc.

The current in the arc varied somewhat during the test, due to the varying asymmetry of the wave and the decay during short-circuit. For this reason several tests were examined under each of the conditions in which decay had apparently occurred, and the average r.m.s.

current during the test was calculated approximately, the values from individual tests under the same conditions showing very good agreement. The values so obtained are given in Table 3, from which it will be seen

variation of the arc path. Although this voltage occasionally showed little variation in tests in which the parallel conductor was not used to control the arc's position, yet in others of the earlier tests the arc voltage

Table 1

SUMMARY OF RESULTS WITH PORCELAIN INSULATORS

1	2	3	4	5	6	7	8	9	10	11
Current	Control	Type A			Type B			Type C		
		Unit	Number of arcs	Arc duration	Unit	Number of arcs	Arc duration	Unit	Number of arcs	Arc duration
amp.				sec.			sec.			sec.
250	None	.1*	>2	1	29	> 5	1	41	5	1
250	None	7	>3	1				44	4	1
250	None	8	>6	1						
250	Electrode	9	1	1	30	1	0.83†	42	1	0.75†
250	Electrode	10	1	1	31	> 5	1	43	3	1
250	Electrode				32	> 5	1	45	3	1
250	Complete	12	1	1	33*	> 1	1	46	>5	1
250	Complete	55	1	1	34	> 5	1	47	4	1
250	Complete	56	1	0.94†	35	1	1	48	4	1
250	Complete				36	> 5	1			
500	None	1*	2	1+0.56†	25*	1	1	39	1	0.8†
500	None	5	1	1	27	>13	1	40	2	1+0.84†
500	None	6	1	0.78†	28	1	1			
500	Electrode	2	1	0.93†	25*	> 1	1	37	1	0.98†
					26	1	0.76†	38	1	0.65†
500	Complete	3	1	0.99†	33*	> 1	1	76	1	0.59†
500	Complete	4	2	1	70	1	0.91†	77	1	0.67†
500	Complete	60	1	1.01†	71	1	1	78	1	0.41†
500	Complete				72	1	0.65†			
1 000	None	11	1	1						
1 000	Complete	57	1	0.73†	67	1	0.74†	73	1	0.43†
1 000	Complete	58	1	0.54†	68	1	0.40†	74	1	0.46†
1 000	Complete	59	1	0.75†	69	1	1.0†	75	1	0.45†
1 000	Complete				81†	1	0.76†			
1 000	Complete				82†	1	0.56†			
1 000	Complete				83†	1	0.70†			
1 000	Complete				84†	1	0.84†			
1 000	Complete				85†	1	0.60†			
1 000	Complete				86†	1	0.57†			
1 000	Complete				87	1	0.78†			
1 000	Complete				88	1	0.76†			
1 000	Complete				89	1	0.76†			

* Information regarding other tests on this unit will be found elsewhere in the same columns.

† The total duration of the arc was in each case $\approx$ 1 sec. The time quoted is the duration of arcing before rupture occurred.

‡ The pin of these units was surrounded with a urea-formaldehyde cement.

> Indicates that the insulator remained without a major break after the number of applications of the arc following the sign.

that the nominal current is not greatly departed from, and is a fair representation of the current to which the insulator has been subjected.

(a) Arc Voltage and Energy.

The maximum and minimum values of the arc voltage were recorded for each test, as they give some idea of the

varied considerably, approaching 20 to 1 in one test. Despite the fact that many more tests were made with the arc controlled by the parallel conductor, the maximum variation was just over 3 to 1, and the average about 2 to 1, apart from tests in which the arc voltage fell to an abnormally low value when the insulator broke.

The arc energy has not been calculated in these tests.

as this quantity is misleading and is only of interest if that proportion of the energy which is dissipated in

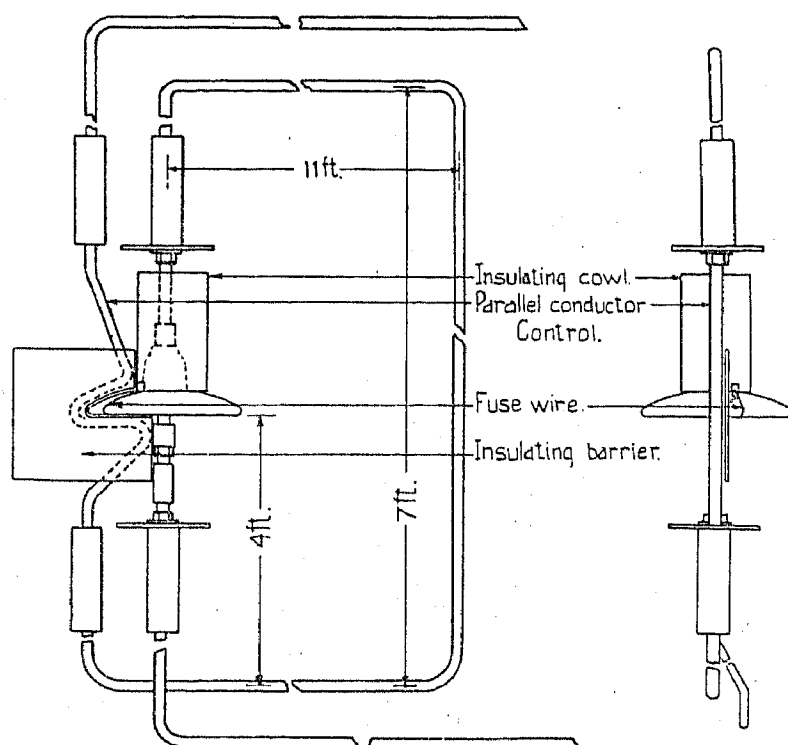


Fig. 8.—Diagram illustrating test set-up.

heating-up the insulator can be calculated. For example, less energy will be used in heating the insulator in the case of an uncontrolled arc requiring a high voltage to main-

tensile and compressive strengths of similar individual samples of ordinary glass or porcelain,* even when the former are apparently free from initial internal stresses, it is not surprising that, when a uniformly applied load is replaced by the mechanical stresses and other thermal effects arising from the action of such a variable disruptive agent as the electric arc, considerable variability is observed between the results obtained when arcs are applied to insulators of the same type. For example, when a controlled 1 000-ampere arc was applied successively to 12 units of Type B porcelain insulator the duration of arcing required to cause rupture varied from 0.4 sec. to 1.0 sec. Also when a controlled 2 000-ampere arc was applied to toughened-glass insulators, 5 of 9 units tested broke after the first application, whereas Unit 20 only broke after the fourth such application.

In view of this variability and the comparatively large number of variables to be investigated, viz. 5 types of insulator, 3 methods of arc control, 5 currents and various durations of the arc, a high degree of precision cannot be expected in the results, despite the fact that over 200 tests have been made, though they do serve to bring out clearly the difference in arc-resisting properties of glass and porcelain insulators under the given test conditions and to show fairly well the effect of different currents in each case.

(c) Position and Cause of Insulator Fracture.

The arc was initially applied on the "west" side of



Fig. 9.—Ciné enlargement showing 500-ampere arc with complete control.

tain it than will be the case when the arc is controlled and retained close to the insulator surface, though the voltage across the latter arc, and hence the energy liberated in it, is much lower.

(b) Variation in Repeat Tests.

As considerable variation is observed between the

the insulator. In 34 cases of fracture of porcelain insulators when the arc was "completely" controlled the insulator broke on this side, while in the remaining 3 cases the shed was completely shattered. Similarly, with electrode control, 9 of the 10 broke on this side.

* See, for example, D. H. ROWLAND: *Electrical Engineering*, 1930, 55, p. 618.

When the arc was uncontrolled, on the other hand, the break occurred more frequently on the "east" side (7 cases out of 9 in which the cause could be determined), owing to the movement of the arc below the insulator. This can be explained by the mutual repulsion between the two portions of the arc above and below the insulator.

metrically opposite, and examination of units which broke as a result of one application of a 500-ampere uncontrolled arc shows that this had occurred in most cases. The test is therefore made more severe by ensuring that the arc remains rooted to the same point on the pin throughout the whole arc duration.



Fig. 10.—Successive ciné enlargements of Test 6045 illustrating, with Fig. 11, correlation of test records.

Change of position can be effected more readily in the hot gas underneath, resulting in the arc root being transferred to the "east" side of the insulator pin. When this movement of the arc root to the "east" side of the insulator and its fixation there occurs, the insulator is to all intents and purposes subjected to an arc having electrode control, the arc roots being in this case dia-

The above figures demonstrate that rupture occurs in most, if not all, cases as a result of heating of the under surface of the insulator. This is well illustrated in Fig. 6, in which it will be seen that the insulator broke at the position of the arc *below* the insulator, which differed in this case by 180° from the position of the burn on the top surface.

Table 2

SUMMARY OF RESULTS WITH GLASS INSULATORS

COMPARISONS WITH PORCELAIN

633

Current	Control	Toughened glass				Pyrex				Toughened glass				Pyrex			
		Unit	Number of applications of arc to cause rupture	Duration of each application	Lag of rupture after arcing	Unit	Number of applications of arc to cause rupture	Duration of each application	Lag of rupture after arcing	Unit	Number of applications of arc to cause rupture	Duration of each application	Lag of rupture after arcing	Unit	Number of applications of arc to cause rupture	Duration of each application	Lag of rupture after arcing
amp. 500	None	15*	> 3	1	—			sec.	min.	amp. 1 000	Complete	116	> 1	sec. 1-26			
500	Electrode	13*	> 2	1	—					1 000	Complete	62	2 ^{¶¶}	1-7			
500	Electrode	14*	> 1	1	—					1 000	Complete	63	2**	2-25			110 sec.
500	Complete	13*	3	1	10 min.	49*	> 1			1 000	Complete	64	1	2-3			(1-83 sec.)
500	Complete	14*	5	1	10 min.					1 000	Complete	65	2 ^{††}	2-2			16 min.
500	Complete	15*	> 2	1	—					1 000	Complete	104	1	2-08			35 sec.
500	Complete	117	1	2-7	13 min.					1 000	Complete	105	1	1-7			1-5 sec.
500	Complete	118	1	2-23	> 0-5 to					1 000	Complete	106	1	2-06			28 min.
					< 1-75 hr.					1 000	Complete	107	1	1-85			25 min.
					40 min.					1 000	Complete	108	1	2-08			2 hr.
					27 hr.					1 000	Complete	109	1	2-6			> 4 hr.
					> 2 hr. [§]					1 000	Complete						18 min.
1 000	Complete	16	≤ 3 ^{††††}	1	1 min.	49*	6 [†]	1	5	2 000	Complete	19	4 ^{††}	0-5			3-5 min.
1 000	Complete	17	3 ^{††††}	1	50 sec.	50	1	1	1	2 000	Complete	20	4 ^{§§}	1			50 sec.
1 000	Complete	18	3 ^{††††}	1	5 min.	51	3 ^{***}	1	2	2 000	Complete	21	1	1			1 min.
1 000	Complete	61	1	1	—					2 000	Complete	22	1	1			5 sec.
1 000	Complete	61	1	2-2	12 min.					2 000	Complete	23	1 [†]	1-19			30 sec.
1 000	Complete	110	> 1	0-75	—					2 000	Complete	122	1	0-95			37 min.
1 000	Complete	111	> 1	> 0-83	—					2 000	Complete	123	> 1	1-01			—
1 000	Complete	112	1	0-90	(0-1)					2 000	Complete	124	> 1	0-99			—
1 000	Complete	113	> 1	1-15	—					2 000	Complete	125	1	1-01			(0-30)
1 000	Complete	114	> 1	1-10	—					2 000	Complete	126	> 1	1-01			—
1 000	Complete	115	> 1	1-26	—					5 000	Complete	24	5 ^{††}	0-35			40 sec.
										5 000	Complete	66	2 ^{¶¶}	≈ 0-5			250 sec.

* Information regarding other tests on this unit will be found elsewhere in same column.

† Unit cracked after second test. (About one year between first and second tests.)

‡ Arc formed through to parallel element in one test.

§ Burst overnight.

|| Insulator broke during arcing.

¶ 30 min. between tests.

** 50 min. between tests.

†† 35 min. between tests.

†† 30, 31 and 21 min. between tests.

§§ 74, 139 and 39 min. between tests.

¶¶ Time between first and last test 4 hours 11 min., minimum interval between tests 26 min.

*** 29 and 21 min. between tests.

††† One year between two of the tests.

††† 33 and 50 min. between tests.

> Indicates that the insulator remained without a major break after the number of applications of the arc following the sign.

(d) Effect of Controlling the Arc on the Rupture of Porcelain Insulators.

Sections (a) to (c) above show that in the present investigation the arc was applied in a much more uniform and reproducible manner to the insulator surface, and

summarized, since even uncontrolled arcs caused fracture of the insulators with this current. When it is further considered that the energy liberation in an uncontrolled arc is found to be some 50 % greater than that in a controlled arc it will be realized that the latter represents

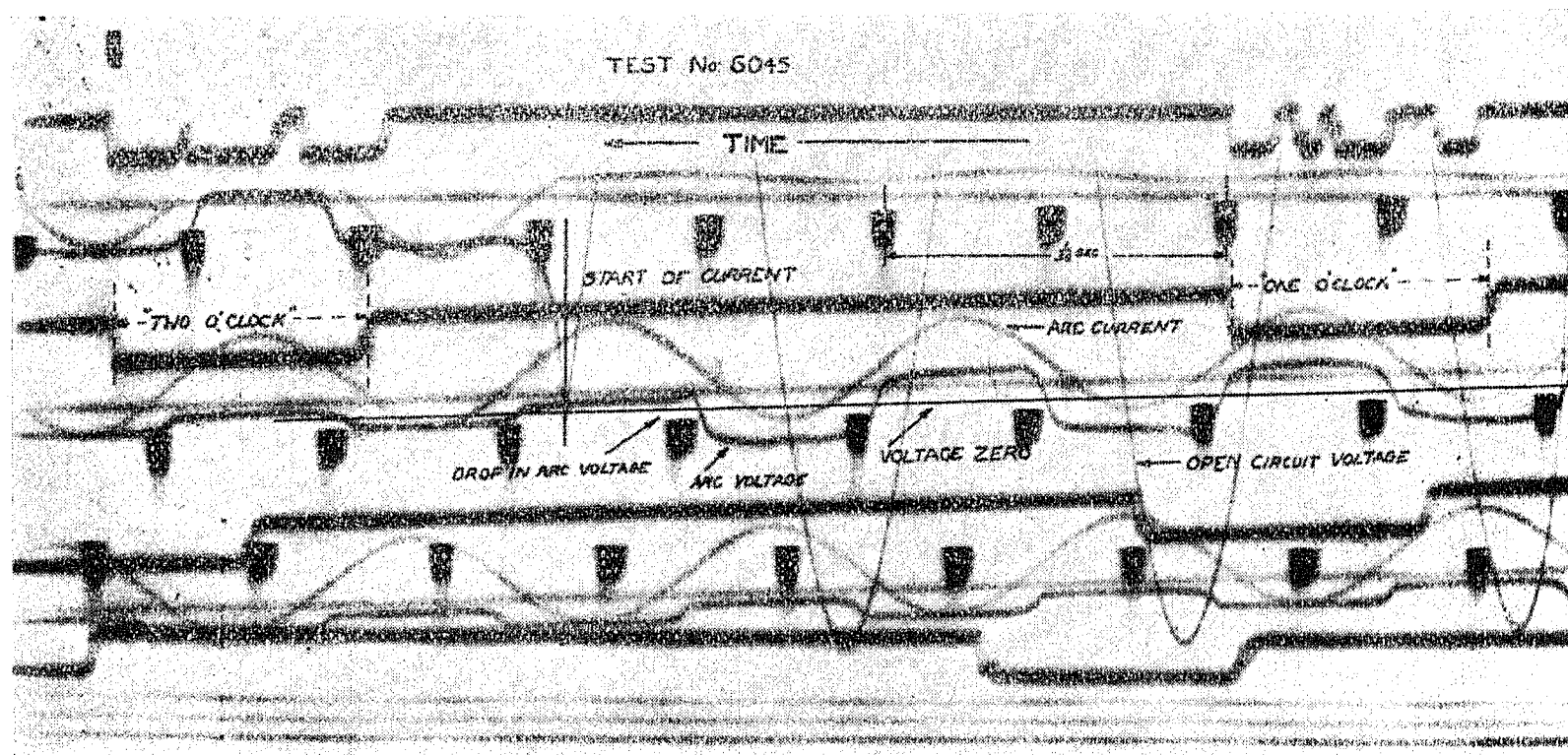


Fig. 11.—Portion of oscillogram of Test 6045.

also suggest that such an application of the arc constitutes a more severe test of the insulator's arc-resisting properties. The latter suggestion is also indicated by the results of comparative tests so far as they go, for whereas no porcelain insulator was broken by the

Table 3

AVERAGE VALUE OF CURRENT CORRESPONDING TO VARIOUS NOMINAL CURRENTS AND ARC DURATIONS

Nominal current	Arc duration	Mean R.M.S. current during arcing
amp.	sec.	amp.
1 000	1	1 070
1 000	2	1 020
2 000	0.5	1 925
2 000	1	1 875
5 000	0.33	5 000
5 000	0.5	4 850

application of an uncontrolled 250-ampere arc to 6 units, 4 out of 8 were broken at the first application of an arc with electrode control and 4 out of 10 by the first application of a completely controlled arc. The increase in severity is less marked in the tests with 500-ampere arcs, as will be seen from Table 4, in which the results are

a relatively much more efficient and severe test, as well as a more uniform and reproducible one.

(e) Conditions of Rupture of Porcelain Insulators.

The minimum current required to cause fracture of single units of all the types of porcelain insulators tested, when applied for 1 sec., is less than the minimum current used (i.e. 250 amperes), almost half the units tested at this current having been broken by the first application of the arc. The minimum current of 1 sec. duration causing fracture of all the units tested thereat, namely, 18, was 1 000 amperes, and one only broke at the end of the arcing period.* The proportions of the different types fractured by single 1-sec. applications of arcs of 250, 500 and 1 000 amperes are shown in Fig. 12, in which are also shown the proportions observed to fracture in under 0.5 and 0.75 sec. respectively.

It is to be noted that in many cases in which observers' comments were that the insulator broke during the test, there is no sign of fracture on the ciné-camera film, indicating that these units had fractured at or just immediately following the cessation of the current. The possibility that the final cause of rupture was the sudden withdrawal of the source of heat in some cases cannot be

* Since it was shown in 4(c) that the cause of rupture was the heating of the under-side of the insulator surface, an attempt was made to minimize this by surrounding the insulator pin with a urea-formaldehyde cement in order that the gas evolved by the action of the arc on this cement might prevent intense localization of the heating. This was done for 6 of the 18 units to which a 1 000-ampere arc was applied for 1 second, but had no effect on the arc duration required to cause rupture.

ruled out. If this were the case, the curves for 0.5 and 0.75 sec. in Fig. 12 would then not be comparable with that for percentage of breakages occurring after 1 sec., since the latter represented current cessation, whereas in the case of the other two arc durations the arc was continuing, the total duration of arcing being in all these cases 1 sec. However, all the values given herein can

(f) Rupture of Toughened-Glass Insulators.

One outstanding feature of the comparison of the rupture of glass and porcelain insulators is the fact that whereas those porcelain units which fracture do so during or immediately after arcing, glass units,* whether toughened or pyrex, broke, with only three exceptions, at intervals after the end of arcing ranging from a few

Table 4

NUMBERS OF PORCELAIN INSULATORS RUPTURED BY ONE APPLICATION OF AN ARC WITH DIFFERENT METHODS OF ARC CONTROL

Current	Control	Type A		Type B		Type C	
		Number tested	Number ruptured by one application	Number tested	Number ruptured by one application	Number tested	Number ruptured by one application
250	None	3	0	1	0	2	0
	Electrode	2	2	3	1	3	1
	Complete	3	3	4	1	3	0
500	None	3	2	3	2	2	1
	Electrode	1	1	2	1	2	2
	Complete	3	2	4	3	3	3

only be regarded as very approximate owing to the variability of the phenomena.

The arc durations required to cause fracture of the individual units are shown plotted in Fig. 13. As has

seconds to 27 hours. The reason for this difference in behaviour is one which might well repay fuller investigation. Meanwhile, it may be pointed out that it is generally believed that glass and porcelain always rupture due to tensional and not to compressive forces, while the

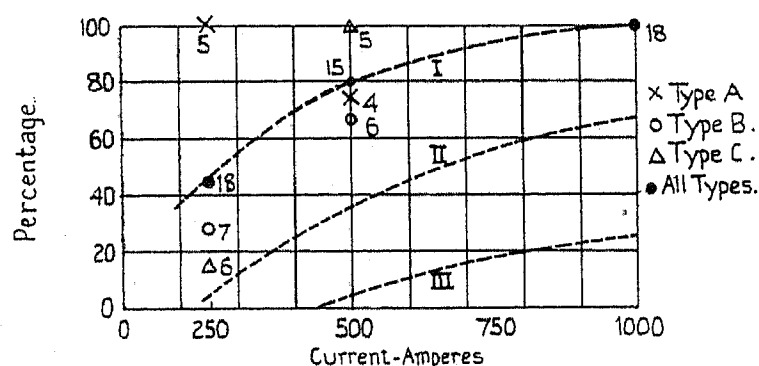


Fig. 12.—Percentage of porcelain insulators fractured after 1 sec. (curve I), after 0.75 sec. (curve II), and after 0.5 sec. (curve III) at different currents with complete or electrode control. Points represent percentage of each make broken after 1 sec., the number attached to each representing the number of units tested.

already been pointed out, several units were unbroken by the application of 250- and 500-ampere arcs for 1 sec., so that the average values of the arc duration cannot be determined for these currents, though in the case of 500-ampere arcs the position of the median arc duration can be determined.

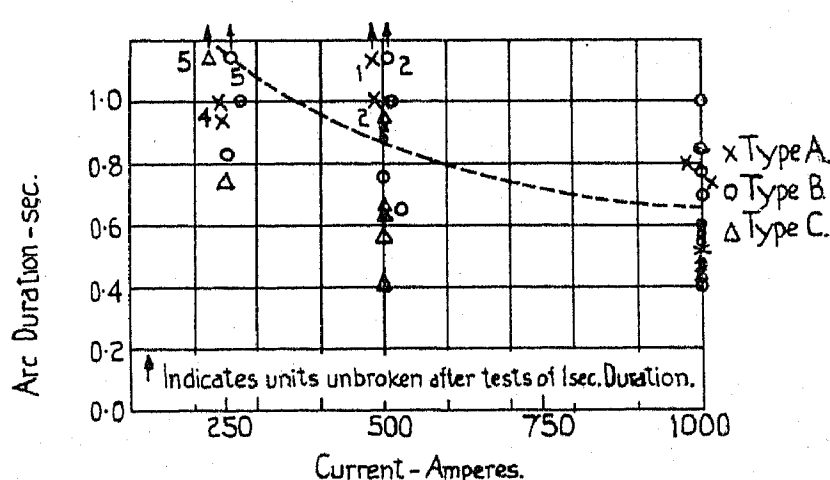


Fig. 13.—Arc duration required to cause fracture of individual porcelain insulators at different currents with complete or electrode control.

effect of surface cracks in initiating fracture is of the greatest importance. During the actual heating of the insulator by the arc, tensional forces will be superimposed on any stresses existing in the inner layers of

* Some tests made by the E.R.A. on annealed-glass insulators in an earlier investigation, not reported herein, showed, for the most part, the same characteristic.

the insulator, whereas during the ensuing cooling period tensional stresses will be superimposed on the stresses of the surface layers. The latter would account for the rupture of the glass insulators, if sufficient to counteract the compressive forces initially existing there, whereas the larger grain and increased chance of irregularity of structure of the porcelain insulators may result in the increased internal tensional stresses being adequate to cause rupture of the porcelain during heating.

The full extent of the complication introduced by this delay in the rupture of glass insulators was only realized during the third and final series of tests. Until then it was believed sufficient to allow about half an hour between successive tests on the same unit, if more than one arc was applied thereto, no unit having fractured more than 16 minutes after the cessation of arcing, during the first two series of tests, while the majority had burst after 5 minutes. However, during the last series of tests on a new batch of insulators one unit broke after

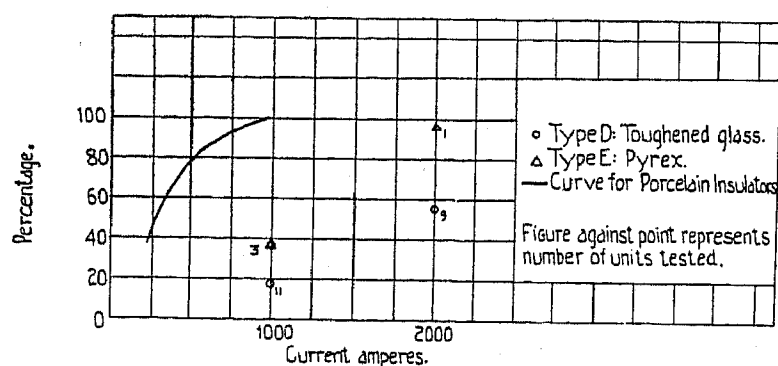


Fig. 14.—Proportion of glass insulators fractured after 1 sec. at different currents with complete control.

the surprisingly long time of 27 hours after arcing. This result rendered one or two of the earlier results doubtful, since sufficient time might not have been allowed to exclude the chance that rupture might have occurred after an earlier test. These are indicated in Fig. 15 and the times between tests are given in Table 2 where necessary.

It will be seen from Figs. 12 and 14 that while the application of a controlled 1 000-ampere arc for 1 sec. caused fracture of all 18 porcelain units to which it was applied, only one of the eleven units of toughened glass so tested failed, and this unit failed during the application of the arc, which may have indicated the existence of an internal fault in this particular unit. The application of a controlled 2 000-ampere arc for 1 sec. only caused rupture of five of the nine toughened-glass units so tested. As regards the effect of a 500-ampere arc for 1 sec. with electrode or complete control (five of the former and ten of the latter), only three of the fifteen porcelain insulators so tested survived, while the three toughened-glass units were unaffected, apart from some fusing and flaking of the surface. Two of the three porcelain units which survived the first arc were tested further, and failed during the second application of the arc. In contrast to this, one of the three toughened-glass units survived the application of three uncontrolled and two completely controlled arcs, another only shattered after five applications of the completely controlled arc following one application of an arc with electrode control, while the third only failed after three applications of a completely controlled arc

and two applications of the arc with electrode control. In all cases sufficient time was allowed between tests to admit of rupture occurring.*

The above results show clearly that the arc-resisting properties of toughened glass are superior to those of porcelain when tested in the manner described, though no precise quantitative comparison can be given on the present data. The average duration of 1 000-ampere controlled arc required to cause rupture of toughened-glass units and the minimum currents required to cause

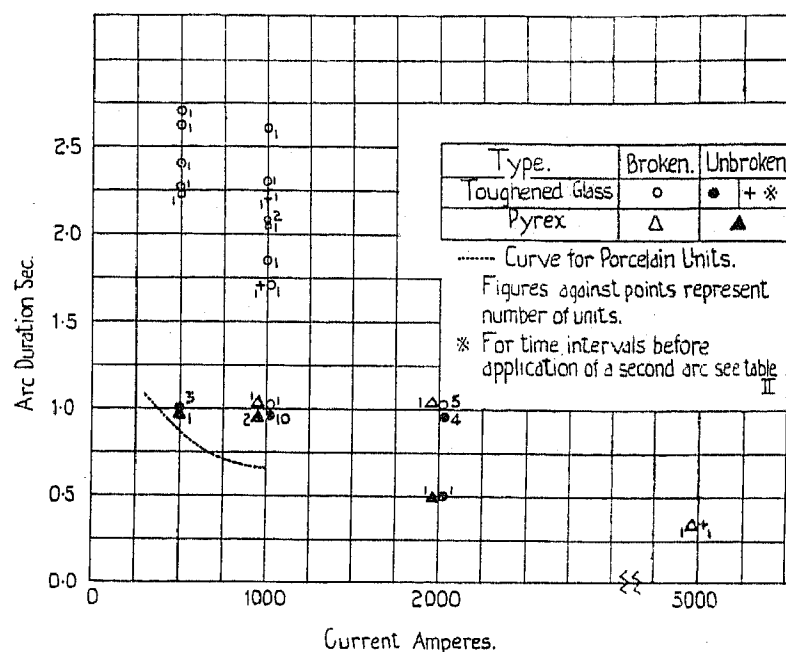


Fig. 15.—Arc duration to cause fracture of individual glass insulators at different currents with one application of completely controlled arc.

rupture of all and any units respectively would all appear to be of the order of quite twice the corresponding values for porcelain units.

The earlier tests suggested that Units 62, 63 and 65 of toughened glass had survived the application of a controlled 1 000-ampere arc for approximately 2 sec.,† the time-intervals between the initial and second "fatal" tests being in each case at least half an hour, and it may be that they actually did so. When an additional group of 6 units were tested, however, with current durations lying between 1.7 and 2.6 sec., all broke at times after arcing ranging from about 1.5 sec. (Unit 104) to more than 4 hours, the time during which the latter unit (108) was under observation. Similarly, a group of 5 tests with a controlled 500-ampere arc applied for times ranging from 2.2 to 2.7 sec. all resulted in rupture of units of the latest batch of insulators, one shattering as long as 27 hours after the application of the arc.

When shattering does not occur the arc has comparatively little effect on the toughened-glass insulators. For example, whereas the corrugations of a porcelain insulator are frequently levelled by a 500-ampere arc in a second, as in Fig. 6, Figs. 16 and 17 show that such an application of the arc has little effect on the glass insulators. Fig.

* The point of application of the arc was not always the same in these tests. Thus to one quadrant of Unit 13 one arc with electrode control only and two with complete control were applied; to a second quadrant one completely controlled arc and to a third one arc with electrode control. To one quadrant of Unit 14 one arc with electrode control and to another five completely controlled arcs were applied.

† There is no appreciable difference between the average currents for arc durations of 1 and 2 seconds (see Table 3).

16(a) shows the thin layer of glass fused off the upper surface of Unit 13.

When shattering of toughened-glass units occurred, the whole insulator had been "cracked" into an irregular

ness was observed in every case. In contrast, 4 porcelain insulators, Units 5, 41, 47 and 48, cracked but remained in position, and 2 pyrex units, 49 and 51, similarly remained in position, though Unit 51 broke to

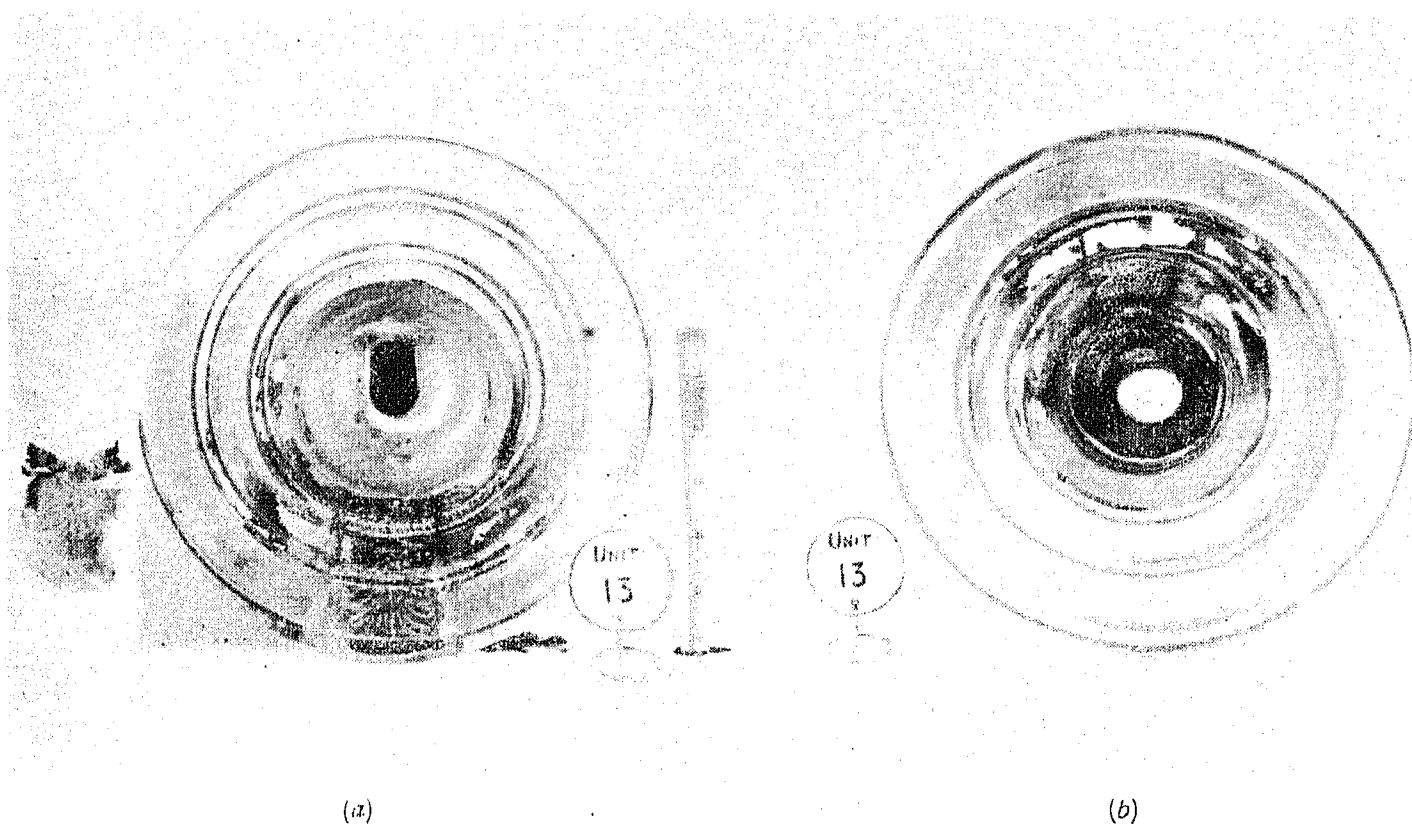


Fig. 16.—Unit 13 after application of 500-ampere arc for 1 sec.

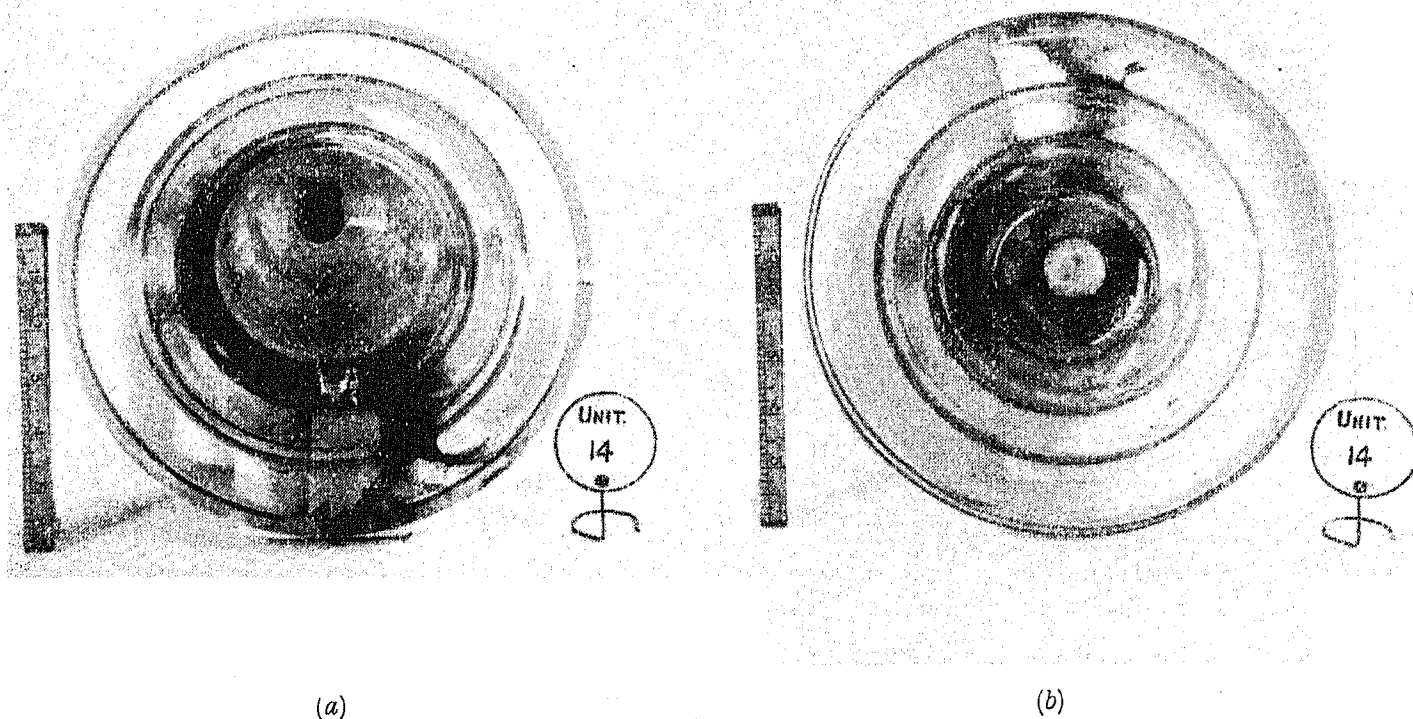


Fig. 17.—Unit 14 after application of 500-ampere arc for 1 sec.

pseudo-crystalline tracery, as is illustrated in the photograph of one of the larger fragments in Fig. 18, while Fig. 19 shows the completeness of the shattering, the fragments being the largest available. Such complete-

the touch after the test, while Unit 49 successfully withstood three further 1 000-ampere arcs, each of 1 sec. duration, before breaking along the crack caused by the second such application. This ease of detection

of damaged units is also in favour of glass units, and this advantage has been emphasized by users of glass insulators in France, in reply to an E.R.A. questionnaire.

is proportional to the product of arc duration and arc current. It will be seen from Figs. 13 and 15, however, that these two quantities are not of equal importance in

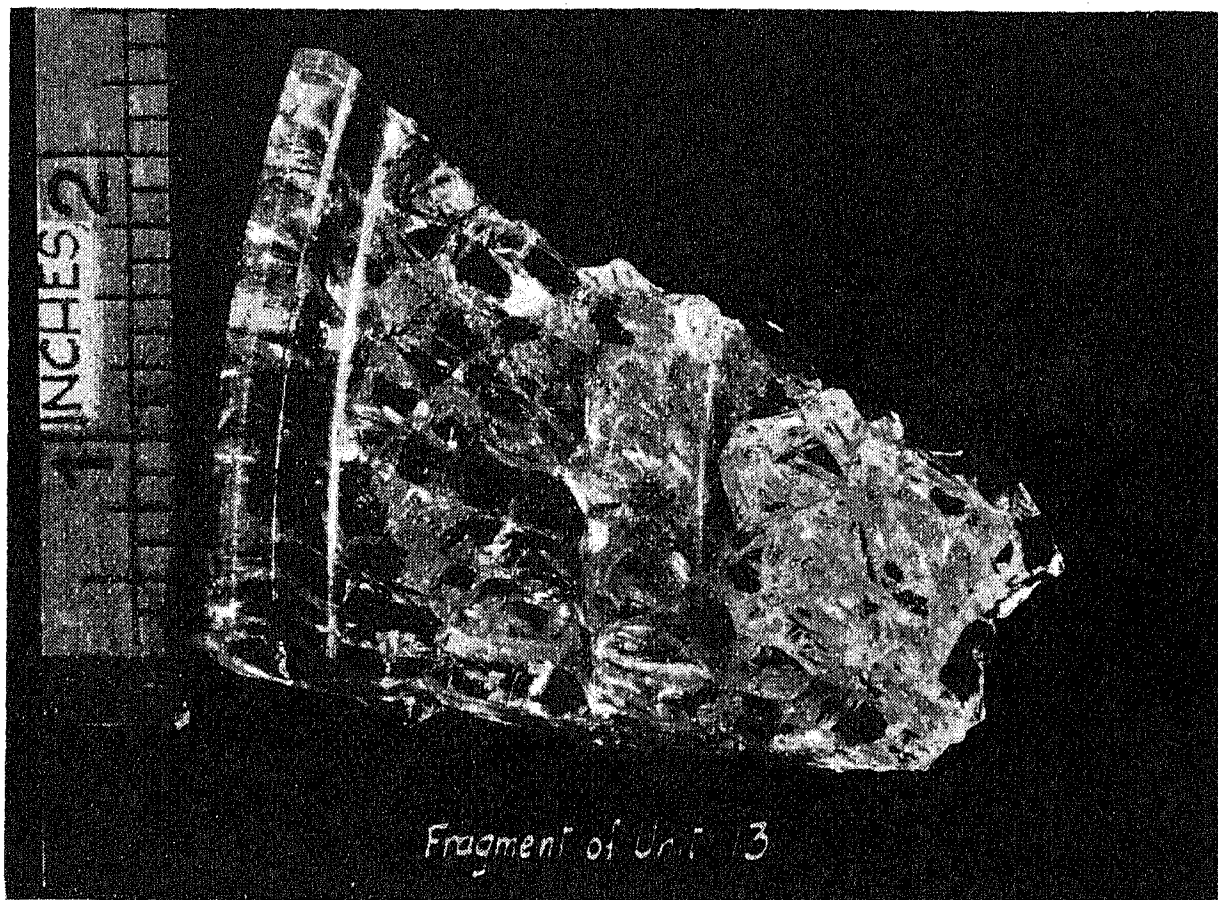


Fig. 18.—Structure of shattered toughened glass.

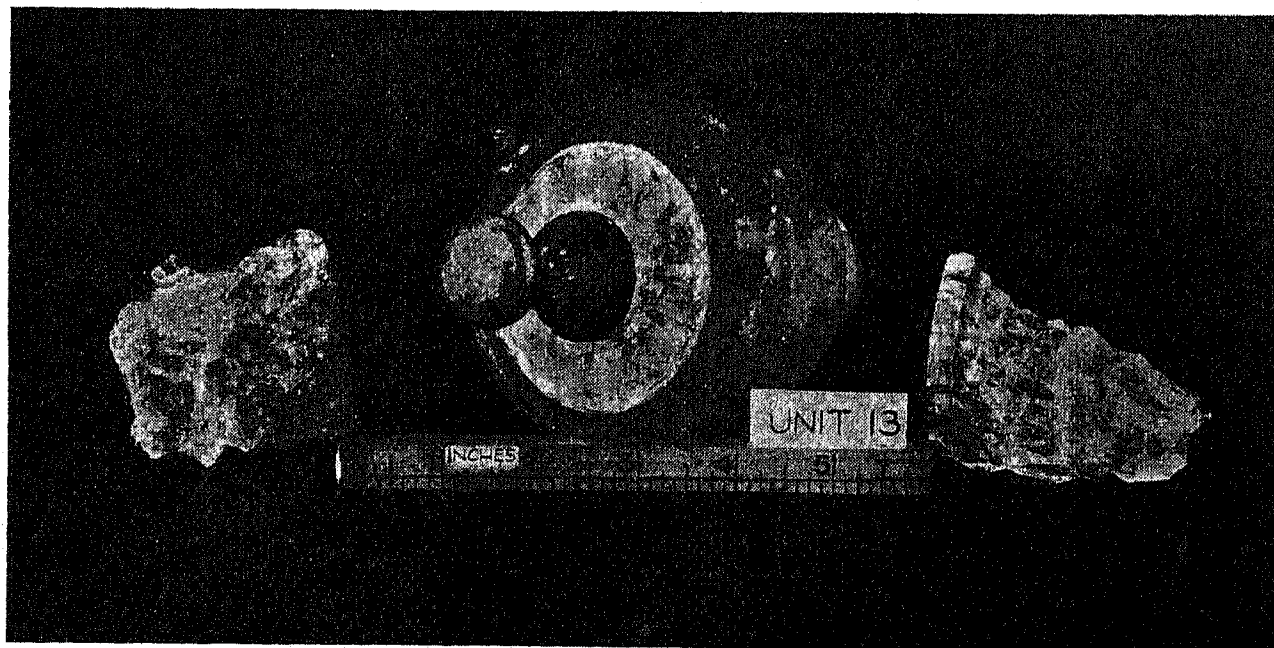


Fig. 19.—Photograph illustrating completeness of shattering of toughened-glass insulators. Unit 13 after five 1-sec. applications of a 500-ampere arc.

(g) Relative Effects of Arc Current and Arc Duration.

Over the range of current investigated the arc voltage is practically independent of the current in the arc,* so that for a given length of arc the arc energy liberated

causing insulator fracture, since the arc duration required to cause breakage is not inversely proportional to the current, but to a power of the current less than 1 in both cases, and probably in the neighbourhood of $\frac{1}{2}$ in the case of porcelain units (Fig. 13). This constitutes a further argument against the use of arc energy as a

* E. B. WEDMORE, W. B. WHITNEY and C. E. R. BRUCE: "An Introduction to Researches in Circuit Breaking," *Journal I.E.E.*, 1929, 67, p. 568.

criterion of effectiveness of an arc in causing insulator fracture. Relatively, the duration of arcing is thus of greater moment than the current in the arc. This result will depend on the degree of contact of the arc at different currents and hence on the method of test adopted. The reduction of this contact at higher currents due to increased bowing of the arc away from the insulator surface as the current increases probably accounts in part for the reduced slope of the curve in Fig. 13. It may also be recalled that the temperature* and current density of these arcs are believed to be approximately constant. The heating of the insulator would then be proportional to the longitudinal cross-section of the diameter of the arc and hence to the square root of the current. However, these considerations are really outside the scope of the present investigation.

(h) Rupture of Pyrex Insulators.

The performance of the only 6 pyrex units available for test appeared to be somewhat less satisfactory than that of toughened glass. For example, with currents of 1 000 amperes one unit broke after one application, one cracked after two applications, and the third broke after three applications, for, as has been said, pyrex also broke after the arc was extinguished, the longest time-lag observed being 5 min. One toughened-glass unit broke during arcing out of 11 to which 1 000-ampere arc was applied for 1 sec., and the 3 units tested to destruction each broke after the third such test. With the applications of 5 000 amperes for $\frac{1}{3}$ sec. to single units of each type the advantage again lies with the toughened glass, another unit of which in addition successfully withstood 5 000 amperes for $\frac{1}{2}$ sec. In the earlier investigation already mentioned pyrex had been shown from the present point of view to be superior to porcelain, and still more to annealed glass.

An interesting feature of the tests on the pyrex units was the effect of the arc on the seal around the pin. Large segments of the seal were excavated by the arc, and in the ciné records molten lead from this region could be seen streaming down from the base of the insulator. The under-surface of the insulator was covered with a grey film which was found on examination to contain lead, while comparatively large splashes of lead were found below the insulator after these tests. Besides affecting the insulating properties of the unit in question as well as that of neighbouring units, such an effect would result in a reduction of the mechanical strength of the string.

(j) Comparison of Test with Working Conditions.

Though the tests described herein from the point of view of the manner of application of the arc represent the worst condition likely to arise in practice, it is to be observed that they differ in one important aspect, namely that the insulators during test were free from any applied mechanical stress, whereas in practice this may amount to several tons in the case of tension strings. What

effect these stresses will have on the arc-resisting properties of the different materials could only be ascertained by tests simulating the conditions obtaining in practice. There is also the probability that more rapid cooling of the surface layers will be produced in practice by rain or wind when the arc is extinguished. Some attempt to simulate such conditions was made in a few tests at the end of the investigation by directing a blast of nitrogen on to the insulator, but the results were inadequate to throw any light on this question.

(4) Conclusions

(1) Owing to the great variability of an uncontrolled power arc a large number of tests would be required to give a reliable comparison between two types of insulator. Some improvement results from causing the arc to remain localized on the cap and pin. A considerable increase in uniformity is achieved by controlling the arc's path by drawing it alongside an insulated conductor carrying the circuit current which is bent as nearly as possible to follow the outline of the insulator (see Fig. 8). This at the same time increases the severity of the test.

(2) With an arc so controlled the insulator always breaks at the point of application of the arc, whereas with an uncontrolled arc rupture usually occurs on the side opposite to the arc's original position, owing to movement thereto of the arc in the hot gas below the insulator, as a result of the mutual repulsion between the two portions of the arc above and below the insulator.

(3) Rupture of the insulator is usually caused by heating of the under-side of the insulator, and the probability of its occurrence is greatly increased if the arc remains fixed to one point on the insulator pin.

(4) The tests indicate that for toughened-glass insulators the minimum completely controlled current that would cause rupture of (a) any and (b) all units when applied for 1 sec., and (c) the average duration of a 1 000-ampere arc required to cause rupture of individual units, are all greater than the corresponding quantities for porcelain insulators and are probably of the order of twice as great.

(5) The present data indicate that pyrex insulators, which an earlier investigation showed to offer much more resistance to fracture by an arc than the other glass and porcelain insulators then available, may be somewhat less satisfactory in this respect than those of toughened glass.

(6) When fracture did not occur the damage to the insulator was less in the case of the toughened-glass insulators tested than in the case of porcelain, the corrugated under-surface of some of the latter survivals being practically levelled off by the arc.

(7) The porcelain units broke during or immediately after the application of the arc, while the glass units, with three exceptions, broke at intervals of from a few seconds to 27 hours after the cessation of arcing. When toughened-glass units failed, the shed shattered completely, whereas four porcelain units and two pyrex units cracked but remained apparently intact, so that a faulty insulator might remain undetected after arcing.

(8) When arcs of 500 and 1 000 amperes respectively were each applied to one pyrex insulator for 1 sec.,

* C. E. R. BRUCE: "An Introduction to Researches in Circuit Breaking, with a Contribution to the Study of the Arc Temperature," *Journal I.E.E.*, 1931, 69, p. 557.

there was little damage to the pyrex itself, but considerable melting and vaporizing of lead in the seal took place on both occasions, which in practice would have had a deleterious effect on the insulating properties of lower sheds, in addition to weakening the mechanical properties of the string.

(9) In testing the effect of power arcs on insulators the use of arc energy as a measure of the severity of the test is liable to be very misleading unless that fraction of the energy which is used in heating the insulator can be determined.

(10) The arc duration required to cause fracture of a given type of insulator in this investigation is not inversely proportional to the current in the arc, but only to a power of the current of the order of $\frac{1}{2}$.

11-kV pin-type insulators were used as listed in Table 5. Sketches of the insulators are given in Figs. 20 to 24. It is to be noted that the two kinds of glass insulators referred to as Type A have their tops sheathed with copper.

Four insulators at a time arranged symmetrically were exposed to the radiation from a 1 500-watt filament lamp surrounded by a polished aluminium reflector, the whole arrangement being screened from draughts while permitting free convection. The intensity of the radiation at each insulator position was determined by replacing the insulator by a horizontal eureka strip blackened on its upper surface. The temperature rise due to the lamp radiation was noted. Direct radiation was then cut off by a polished aluminium shield lagged to prevent it from

Table 5

DESCRIPTION AND IDENTIFICATION OF INSULATORS

Number of specimens		Description	Diagram	Identification letters
Temperature tests	Impact tests			
2	12	One-piece brown porcelain, 11 kV	20	BP1
4	18	Two-piece brown porcelain, 11 kV	21 (a)	BP2
	8	Two-piece brown porcelain, 33 kV	21 (b)	BP3
4	4	Two-piece white porcelain, 11 kV	21 (a)	WP2
3	5	Two-piece bottle glass (annealed), Type A, 11 kV ..	22	BG2 (A)
3	21	Two-piece toughened glass, Type A, 11 kV	22	APG (A)
3	5	Two-piece bottle glass (annealed), Type B, 11 kV ..	23	BG2 (B)
3	5	Two-piece toughened glass, Type B, 11 kV	23	APG (B)
2	17	One-piece pyrex glass	24	PG

PART 2

THE HEATING OF INSULATORS BY SOLAR RADIATION

(1) Conditions of Exposure

B.S. No. 137 for Porcelain Insulators includes a temperature-cycle test designed to ensure that the insulators will not fail in service by cracking due to sudden changes of temperature. The insulator, at a temperature of 70° C., is rapidly cooled to 0° C., and is then required to withstand the voltage test at room temperature. The heating, cooling and voltage test is repeated three times.

This temperature-cycle test was too drastic for annealed-glass insulators and the question arose as to whether it needed modification for application to glass insulators, since there was the possibility that glass would not heat-up to the same degree as porcelain when exposed to solar radiation* and might not be subject to temperature stresses of equal severity in service. Subsequent to this investigation, however, it has been understood that the new "toughened" glass will satisfactorily pass the test.

* Littleton and Shaver (*Journal of the American Ceramic Society*, 1926, 9, p. 618) compared the temperature rises of porcelain and pyrex insulators exposed to concentrated solar radiation and found the mean ratio of porcelain to pyrex was 3.5. The reflected solar radiation was, however, incident on the base and sides of the insulators. This arrangement gives a higher ratio of exposed surface to volume and would thus lead to a relatively higher rise of temperature of the porcelain than would be obtained when radiation is incident only from above.

radiating to the strip, while the latter was heated by an electric current and the watt input found which gave the same temperature rise. In this way the radiation intensity was found to vary between 0.122 and 0.167

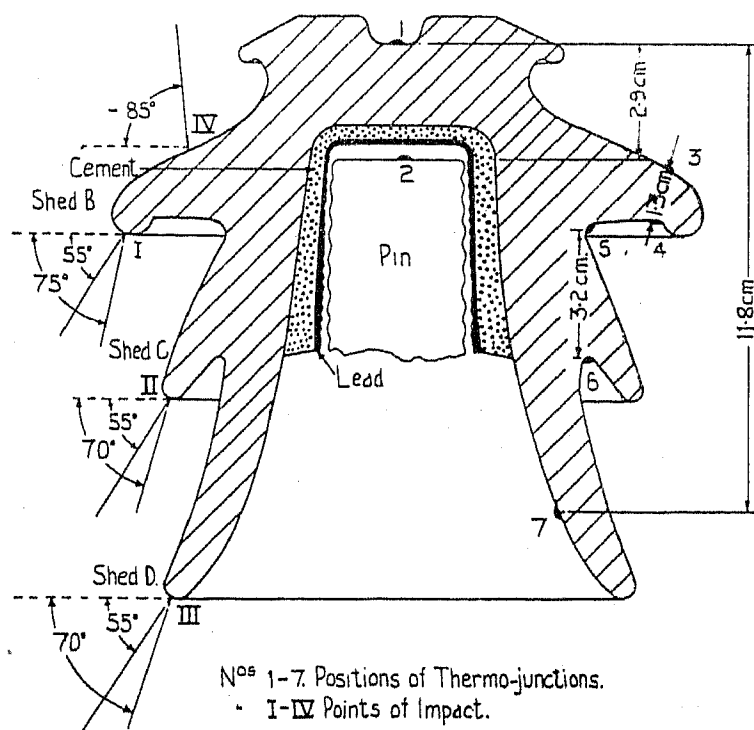


Fig. 20.—One-piece brown porcelain insulator (B.P.1.).

watt/cm²* for the four positions, the mean being 0.147 watt/cm².

The distribution of the energy according to wavelength for solar† and lamp‡ radiation is shown in Fig. 25. Based on data on the absorption§ of glasses, curves are given showing the variation with wavelength of the per-

but they are of interest inasmuch as that they indicate that in a clean condition, insulators of the bottle-glass type would probably have a higher temperature under solar radiation than the other types owing to the higher absorption. Glass similar to window glass, however, has a lower absorption for shorter wavelengths as com-

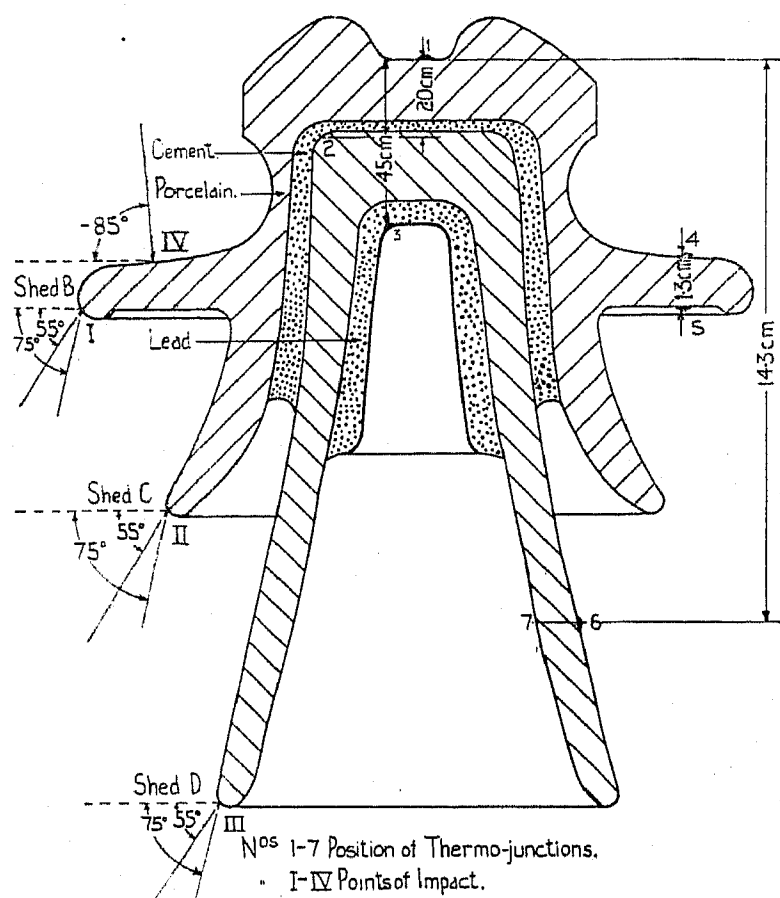


Fig. 21(a).—Two-piece porcelain insulator (B.P.2 and W.P.2).

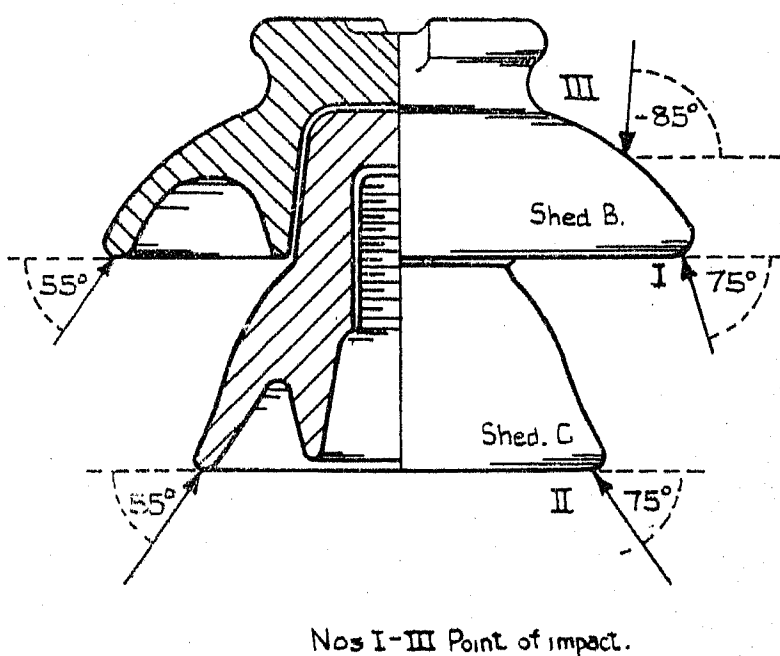


Fig. 21(b).—Two-piece brown porcelain insulator (B.P.3).

centage of incident radiation absorbed on passing through 6-mm thicknesses of different glasses. These curves do not necessarily correspond to the glass used for insulators,

* This variation is due to the fact that the lamp filament was not a complete circle.

† Based on black body at 6 000° K.

‡ Data supplied by G.E.C. for filament temperature of 3 000° K.

§ *Glastechnische Tabellen*, 1932, pp. 461-464.

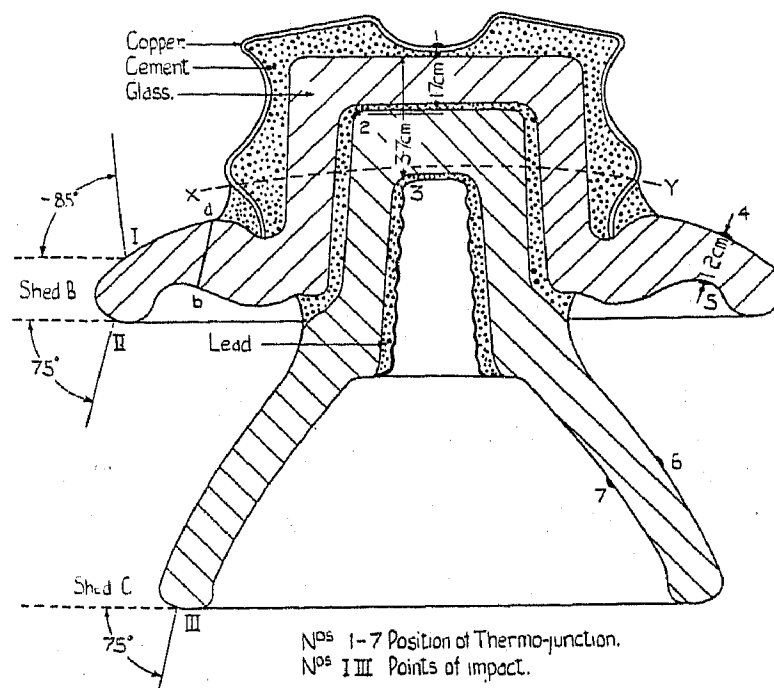


Fig. 22.—Two-piece glass insulator (Type A) B.G.2 (A) and A.P.G. (A).

pared with bottle glass and would thus have a relatively lower temperature-rise. It is probable, however, that a very slight contamination of the surface would tend to counterbalance this effect.

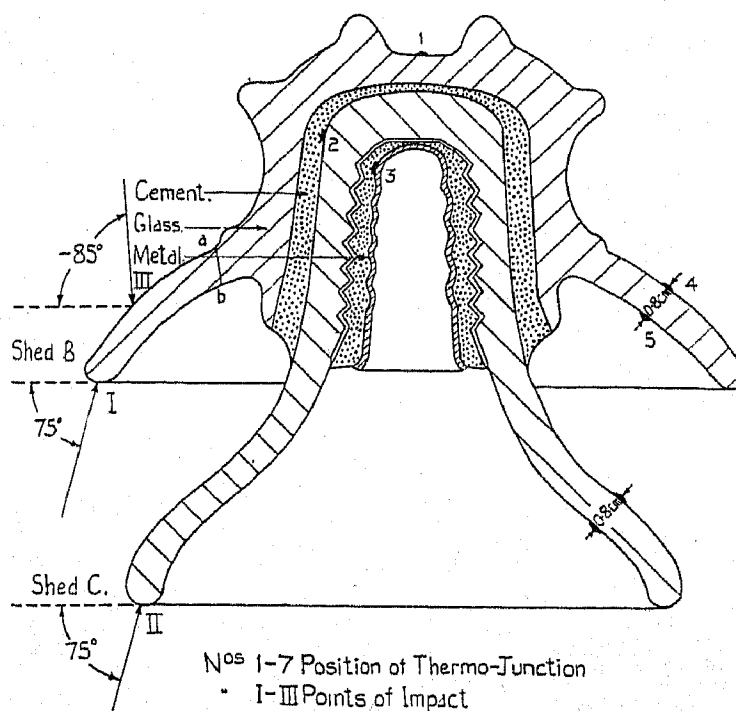


Fig. 23.—Two-piece glass insulator (Type B) B.G.2 A.P.G. (B).

A curve is also given of the reflectivity of ϵ which indicates that there is a small relative higher-frequency radiation from the lamp reflector. This would tend to produce

* Based on values given in International Critical Tables.

temperature-rises of the glasses which have a higher absorption of high-frequency radiation as compared with the effect of solar radiation.

The temperatures (T_a) were determined by thermo-

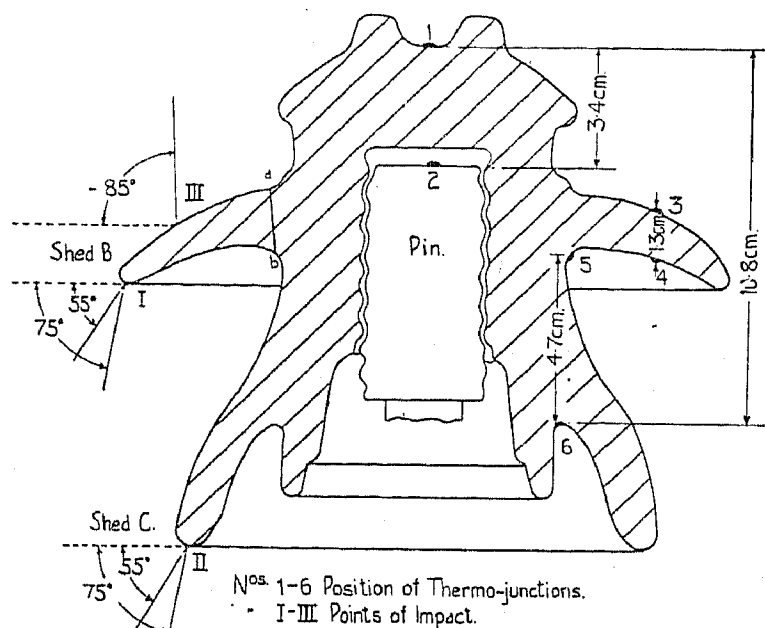


Fig. 24.—One-piece glass insulator P.G.

junctions at points on or in the insulators shown in Figs. 20 to 24, but it was necessary to correct these for variation of radiation intensity W and the equivalent surround temperature (T_e). The latter is not the shade temperature, but is the resultant temperature at any given point due to the combined effect of the surrounding objects (which

will be at various temperatures) and will be the same as that assumed by an object at that point, shielded only from all direct radiation.* Such an object was the eureka strip when shielded and with no current passing, and the values of T_e were so found. Temperatures T_e corrected to a radiation intensity of 0.147 watt/cm^2 and an equivalent surround temperature were accordingly expressed as

$$T_c - T_e = 0.147 (T_a - T_e)/W$$

Stable conditions were attained in about 5 hours.

(2) Temperatures attained by Insulators

The mean values corrected as described are compared in the form of two block charts in Fig. 26. The upper chart corresponds to clean insulators together with clear extensions in the case of B.P.1, B.P.2, B.G.2(A) and A.P.G.(A) to represent the effect of a thin coating of dust from exposure to the atmosphere in an urban industrial area. The lower chart corresponds to insulators to which a thick adherent deposit of soot and coal dust has been artificially applied by spraying with a xylene suspension.

The differences of temperature existing between external and internal points in the insulators are given in Table 6. A study of these differences, together with the distances between the corresponding points, enables an estimate to be made of the maximum temperature gradients likely to arise.

In considering the possibility of a reduction of the

* This conception was employed in E.R.A. Report Ref. F/T44: "Heating of Cables in Racks," by E. B. Wedmore.

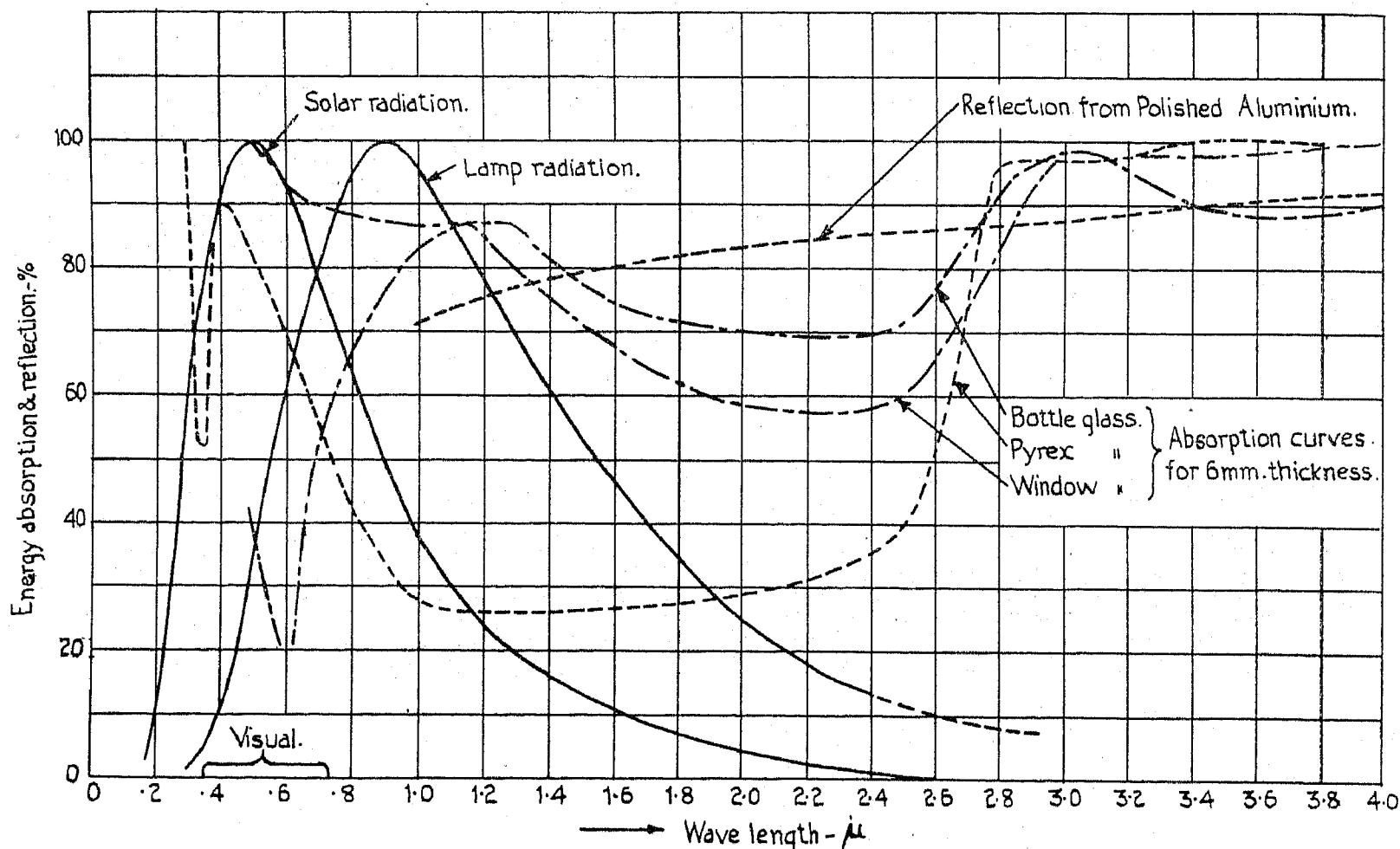
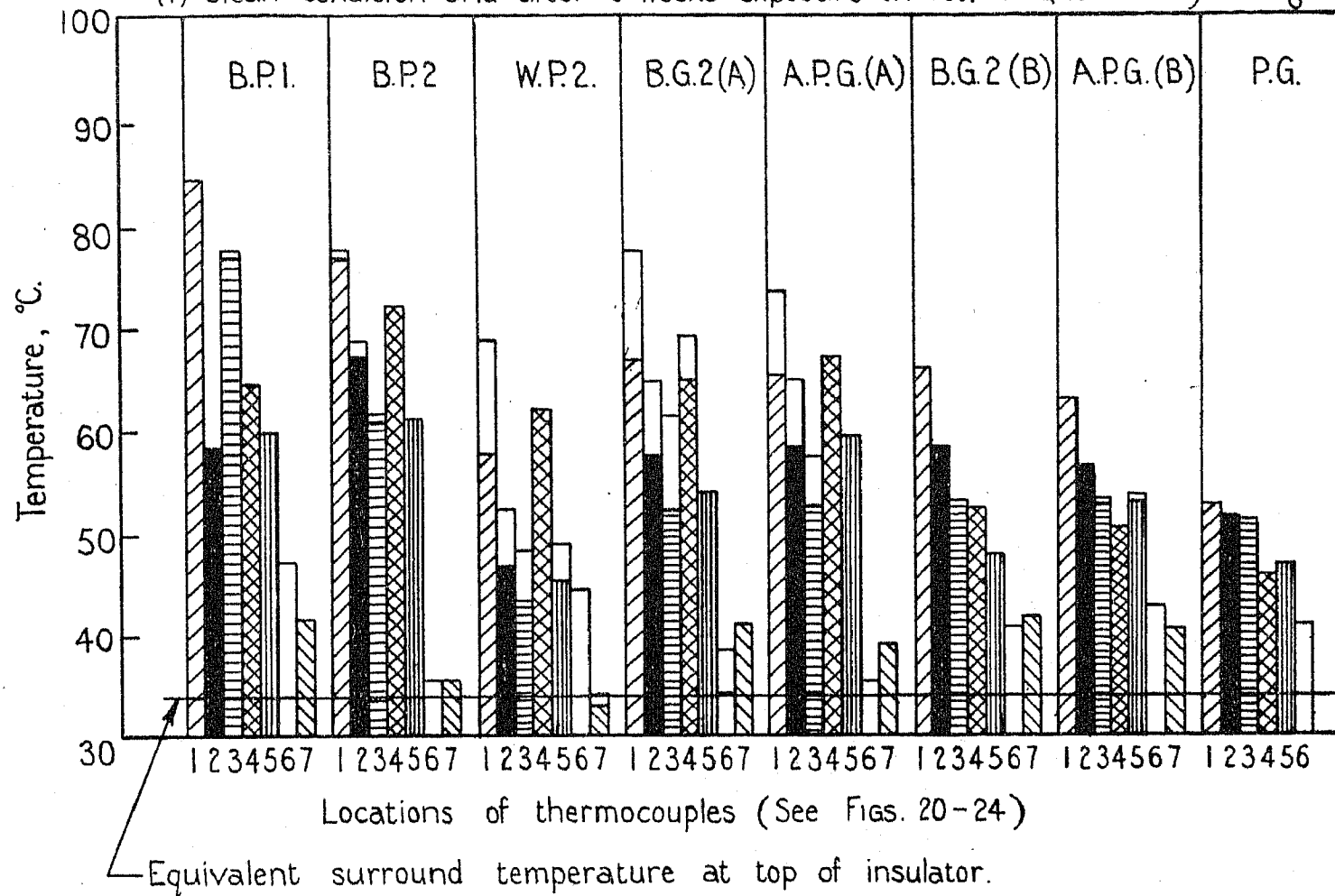


Fig. 25.—Energy distribution in spectrum of solar and lamp radiation, absorption of glasses and reflection from polished aluminium.

(i) Clean condition and after 6 weeks exposure on roof of Queen Mary College.



(2). After application of deposit.

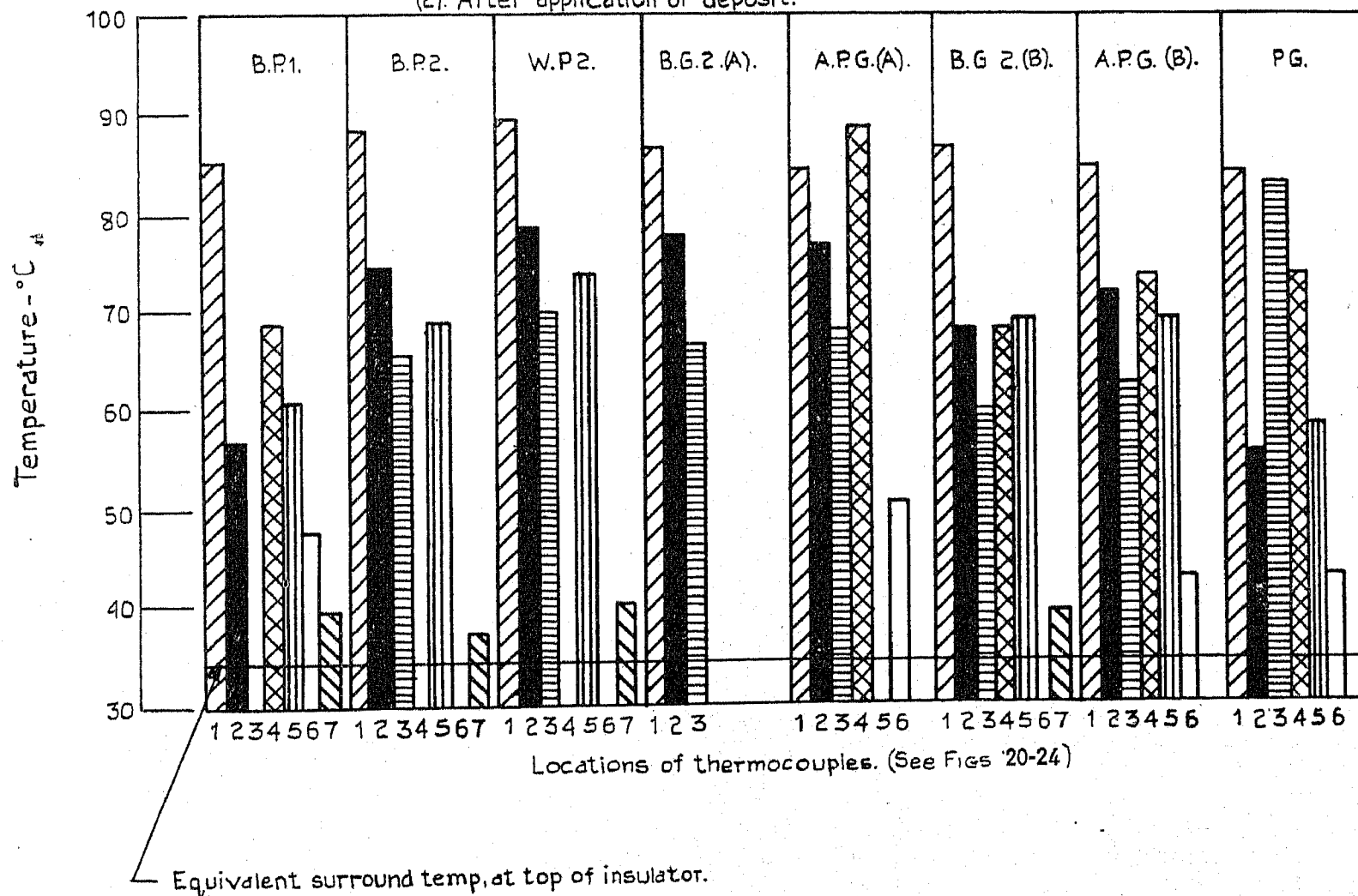


Fig. 26.—Chart showing temperature variation across insulators.

temperature specified in the British Standard Specification test it is necessary to take into account the temperatures attained by porcelain and glass insulators when exposed to the same conditions and in addition the temperature gradients present in the insulators. The maximum temperatures attained by the insulators for

made for surface contamination. On the other hand, for insulators operating under clean conditions, comparative figures may be considered, as follows:—

Assuming that the top of the clean one-piece brown porcelain insulator attains a temperature of 70° C., the tops of the other insulators under the same conditions

Table 6
HIGHEST OBSERVED TEMPERATURE GRADIENTS

Type of insulator	Condition					
	Clean		Thin dust coating		Thick dust coating	
	Location (position on diagram)	Temperature, gradient, deg. C./cm.	Location (position on diagram)	Temperature, gradient, deg. C./cm.	Location (position on diagram)	Temperature, gradient, deg. C./cm.
B.P.1	3-4	12.2*	1-2	3.8	1-2	11.1
B.P.2	4-5	8.3*	—	—	1-2	7.0
W.P.2	4-5	12.9	1-2	7.9	1-2	5.8
B.G.2 (A)	4-5	5.4*†	1-2	7.2	1-2	5.5
A.P.G. (A)	4-5	4.5†	1-2	5.6	1-2	4.8
B.G.2 (B)	1-3	5.7 (approx.)‡	—	—	1-2	12.5 (approx.)‡
A.P.G. (B)	1-3	4.7 (approx.)‡	—	—	1-3	10 (approx.)‡
P.G.	3-4	4.2*	—	—	1-2	10.5

* In direct line with lamp filament. † Not in direct line with lamp filament. ‡ Approximate owing to slight uncertainty of position of thermo-junction.

any given incident radiation intensity (with an equivalent surround temperature of 20° C.) have been calculated by application of the equations given in the Appendix, from the actual temperatures obtained in the tests both for the clean and blackened surface condition (see Figs. 27 and 28). The variation of the temperature

will attain temperatures as shown in Table 7 (taken from Fig. 27).

Taking into account, therefore, that the temperature gradients in the glass insulators are less than in the porcelain, the figures in Table 6 show that, provided the

Table 7
COMPARISON OF TEMPERATURES ATTAINED BY CLEAN INSULATORS EXPOSED TO SAME CONDITIONS

Insulator	Temperature attained, ° C.
One-piece brown porcelain	70
Two-piece brown porcelain	62
Two-piece white porcelain	48
Two-piece bottle glass with copper top ..	52
Two-piece toughened glass with copper top	52
Two-piece bottle glass (no copper top) ..	52.5
Two-piece toughened glass (no copper top)	51.5
Pyrex glass	38

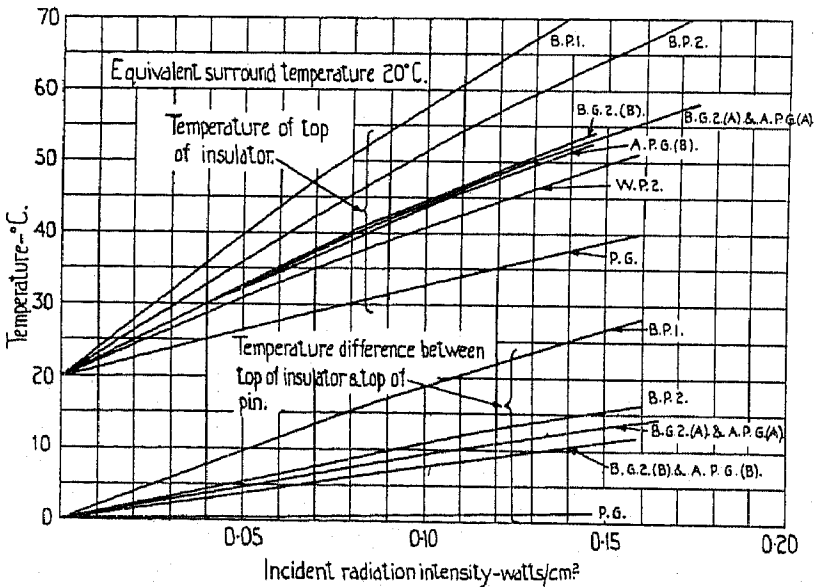


Fig. 27.—Temperatures and temperature differences in clean insulators as function of incident radiation.

differences between top and pin are also given in these Figures. The effect of the surface deposit is to produce equal surface temperatures, and it may be stated at once that since the differences in the temperature gradients are not large, there are no grounds for suggesting an alteration of the specified test temperature of 70° C. as given in B.S. No. 137, if allowance is to be

surface of the insulators is kept clean, the glass insulators will not be subject to thermal stresses to the same extent as the brown porcelain insulators. At the same time, however, the white porcelain insulators experience a rise of temperature slightly less than the glass insulators. The theoretical calculations given in the Appendix indicate that the explanation of the low rise in tempera-

ture of the white porcelain insulators is due to a high reflective power together with a relatively high conductance.

A second fact of interest is the high temperature-rise of the one-piece brown porcelain insulators, supplied by one manufacturer as compared with the lower rise shown by the two-piece brown porcelain insulators from another manufacturer. The values given in Tables 15 and 16 indicate that the difference is due to the very low surface reflecting power of the former type. This suggests that the glazes on the two types of insulators differ, causing the surface of the brown one-piece insulators to have a high absorptive power for incident radiation.

With regard to pyrex insulators, since pyrex glass is essentially a material with a very low thermal expansion

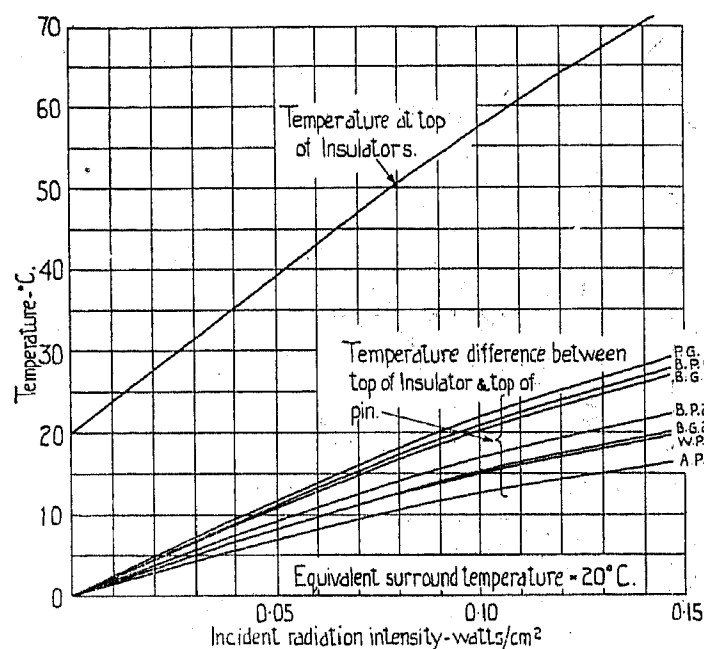


Fig. 28.—Temperatures and temperature differences in insulators with black deposit as function of incident radiation.

the B.S. temperature test is passed without difficulty, but it is of interest to note the low rise of temperature due to low absorption. It may also be noted that no appreciable differences from a thermal point of view exist between bottle-glass and toughened-glass insulators, with or without copper-sheathed tops.

It has been suggested that, in practice, it sometimes happens that the upper surface of the sheds remains clean, owing to the washing action of rain, whilst the under-surface becomes coated with dust deposits. The time available did not permit this condition to be investigated in detail. A little consideration will show, however, that the temperature rises of the porcelain insulators would differ slightly, if at all, from those found for the clean condition. In the case of the glass insulators, an absorbent coating on the under-surface of the shed would tend to produce thermal conditions similar to that of the top of the insulators of the type B.G.2(B), i.e. those without copper tops. Thus, the mean temperatures of the upper sheds would be intermediate between the values found for the clean and thickly-coated conditions, and the temperature difference between the upper and lower surfaces would be not more than 6 deg. C., but probably 1–2 deg. C. less.

PART 3

IMPACT RESISTANCE OF INSULATORS

(1) Conditions of Striking an Insulator

The record throw of a cricket ball is 140 yards; on the basis of a throw of 100 yards projected at 45° the energy at impact of a 5-oz. stone would be about 560 kg.-cm. It may be deduced from the usual ballistic formulae that, for angles of impact between + 55° and + 75° (rising missiles) and also about – 85° (falling missiles) and assuming a height of insulator of 25 ft. (where damage is more frequently experienced) together with an angle of elevation from the thrower of 60° (probable from physiological considerations), then a relatively wide range of angles and velocities of projection will succeed in striking the insulator. Assuming, therefore, these angles of impact, Table 8 shows the impact energies of a 5-oz. stone (142 g.) for throwers at various distances.

Table 8

IMPACT ENERGY OF 5-OZ. (142 G.) STONE

Angle of impact	Angle of elevation	Horizontal distance of thrower, m.	Impact energy in cm.-kg. (1 cm.-kg. = 0.072 ft.-lb.)
– 85°	85°	0.53	22.4
	70°	2.22	60.4
	50°	5.10	457
+ 75°	85°	0.53	5.77
	80°	1.08	30.6
+ 55°	85°	0.53	1.06
	70°	2.22	22.4
	60°	3.53	95.3

Furthermore, for a given position of a thrower a fast low-trajectory missile permits greater tolerance in aim and speed than a dropping missile, so that a downward blow on the top shed of an insulator is relatively unlikely.

The impact testing apparatus, Fig. 29, was of the pendulum type, the missile swinging on a silk fishing line of length 185 cm. against a circular scale not exceeding 60° of arc in order to ensure an adequate tension at the point of release. The insulator was bolted into a heavy wooden framework capable of adjustment to give the necessary angles and positions of impact. The bobs, which were of case-hardened steel, weighed 530 g., 300 g. (250 g. pointed), and 100 g. respectively, giving corresponding ranges of impact energy of 3–10, 9–30, and 15.9–53 cm.-kg. respectively. The shape of the pointed bobs is indicated in Fig. 30; the points became rounded after one or two impacts, and the broken line shows the shape during the majority of the tests. The rounded bobs of 100 g. and 530 g. were spheres of 3 and 5 cm. diameter respectively, while the 300 g. rounded bob was a hemisphere of 4 cm. diameter.

The first blow and increments of energy in successive blows were varied for the different types of insulators so as to give fracture in about 3 to 5 blows except for

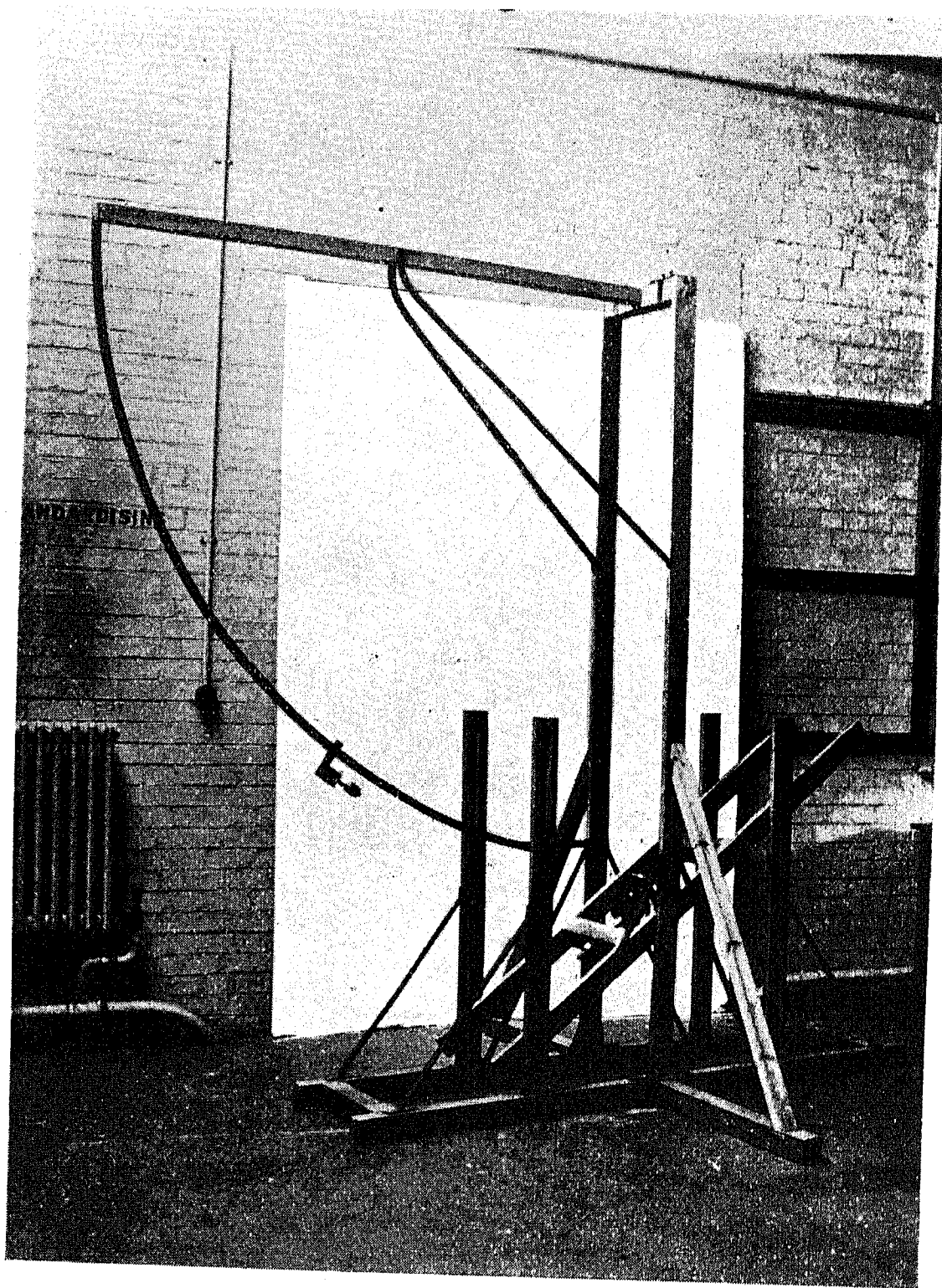


Fig. 29.—Apparatus for impact tests.

very weak parts. The alternative method of applying excessive blows and of measuring the residual energy of pendulum and chips was hardly practicable and has been shown to be erroneous in some cases.* The points of impact are numbered I, II, III and IV in Figs. 20–24.

(2) Fracture of Insulators

(a) Energies Producing Fracture.

Table 5 gives the insulators tested. Tables 9 and 10 summarize the observed fracturing energies for pointed and rounded bobs respectively. Toughened-glass insulators are much more resistant to rounded missiles than pointed missiles, as is to be expected, while the shape of the missile has little effect on porcelain. Nevertheless,

* E. G. BAILEY: "Impact Test—Effect of Rapid Loading on Composite and Fibrous Insulating Materials" (Report Ref. A/T59).

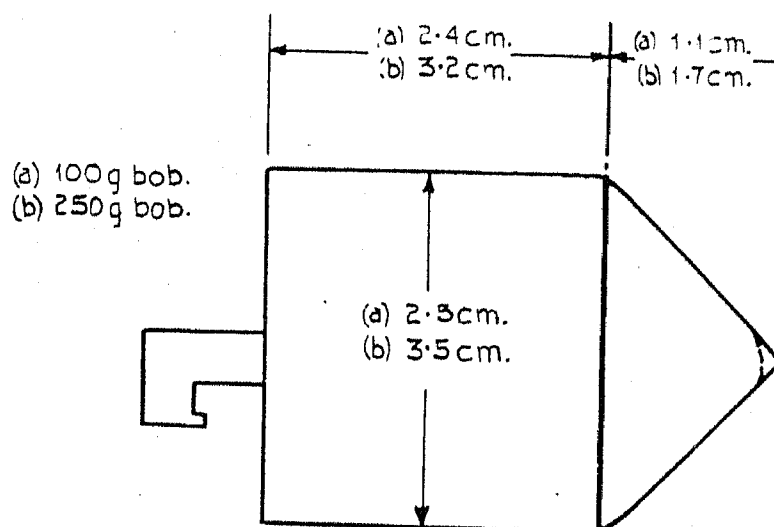


Fig. 30.—Design and dimensions of pointed bobs.

Table 9

RESULTS OF IMPACT TESTS WITH POINTED STRIKER

(1 cm.-kg. = 0.072 ft.-lb.)

Type of insulator	Angle of impact	Shed fractured														
		B					C					D				
		Mean fracturing energy	No. of tests	No. of insulators tested	Max. min. fracturing energy	No. of blows before fracture	Mean fracturing energy	No. of tests	No. of insulators tested	Max. min. fracturing energy	No. of blows before fracture	Mean fracturing energy	No. of tests	No. of insulators tested	Max. min. fracturing energy	No. of blows before fracture
	deg.	cm.-kg.			cm.-kg.		cm.-kg.			cm.-kg.		cm.-kg.			cm.-kg.	
B.P.1	↑	5.0	4	2	{ 10.0* 5.0*†	8 3										
	—85	6.8	6	1	{ 7.5* 4.0*†	10 2										
B.P.2	↓	8.3	7	2	{ 12.0* 5.0*	2 3										
B.P.3	—75¶	24.0	4	2	{ 30.0* 15.0*	5 3										
W.P.2	↑	4.2	5	2	{ 5.0* 4.0*	3 2										
A.P.G.(A)	—85	15.6	5	3	{ 24.0* 10.5*	11 1										
A.P.G.(B)		10.0	1	1	{ 10.0* 4.0*	15 5										
P.G.		3.0	6	2	{ 2.5* 9.0*	3 7										
B.G.2(A)		7.5	4	3	{ 4.0*	3										
B.G.2(B)	↓	—	—	—	—	—										
B.P.1	↑	3.0	3	1	{ 8.0§ 6.0§†	6 4	3.2	16	3	{ 5.5§ 1.6§	10 1	4.4	17	4	{ 10.0§ 2.0§	15 1
		6.3	6	1	{ 4.0§ 2.0§†	6 1										
B.P.2		13.2	13	3	{ 18.0§ 7.0§	5 5	2.1	12	3	{ 3.0§ 1.0§	3 1	3.6	9	2	{ 4.0§ 2.5§	4 2
B.P.3		4.5	6	2	{ 5.5§ 4.0§	6 2	3.0	3	1	{ 3.0§ 3.0§	1 1	—	—	—	—	—
W.P.2	+75	7.5	8	2	{ 9.0§ 4.0§	7 2	1.9	8	2	{ 2.5§ 1.5§	4 1	4.2	10	2	{ 5.0§ 3.0§	5 1
A.P.G.(A)		7.2	26	3	{ 15.0* 5.0§	9 5	6.0	10	4	{ 8.5§ 4.0*	7 2	—	—	—	—	—
A.P.G.(B)		5.3	10	3	{ 7.5§ 3.5§	11 3	3.8	8	4	{ 6.0§ 3.0§	7 2	—	—	—	—	—
P.G.		4.3	17	4	{ 5.5* 3.0*	6 1	5.1	17	5	{ 9.0§ 3.0*	8 2	—	—	—	—	—
B.G.2(A)		6.4	14	3	{ 10.0§ 4.0*	8 2	5.4	11	2	{ 7.0* 3.0*	5 1	—	—	—	—	—
B.G.2(B)	↓	4.8	13	4	{ 10.0* 3.0*	12 1	4.2	14	4	{ 6.0* 2.5§	2 7	—	—	—	—	—
B.P.1	↑	3.0	4	2	{ 10.0§ 5.0§†	8 2	4.5	6	2	{ 6.0§ 4.0§	7 2	6.4	6	3	{ 10.0§ 4.0§	8 3
		7.3	9	1	{ 3.0 2.0†	3 1										
B.P.2		12.2	13	3	{ 16.5§ 9.0§	3 1	2.0	15	3	{ 3.5§ 1.0§	6 1	5.3	8	2	{ 7.0§ 4.0§	5 2
B.P.3		12.2	2	2	{ 18.0§ 9.0§	4 1	4.0	3	1	{ 5.0§ 3.0§	3 1	—	—	—	—	—
W.P.2	+55	6.6	7	1	{ 9.0§ 5.0§	6 1	2.0	9	2	{ 4.0§ 1.0§	2 1	7.5	8	2	{ 9.0§ 6.0§	4 4
A.P.G.(A)		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
A.P.G.(B)		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
P.G.		5.3	17	3	{ 9.5§ 3.5*	9 2	5.4	15	5	{ 8.5* 3.5§	7 2	—	—	—	—	—
B.G.2(A)		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
B.G.2(B)	↓	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

* Piece broke out of insulator shed.
§ Insulator shed was chipped.

† See Fig. 1. Corresponds to thicker shed.
|| + 70° for sheds C and D.

‡ See Fig. 1. Corresponds to thinner shed.
¶ Striker slipped at larger negative angles.

Table 10
RESULTS OF IMPACT TESTS WITH SPHERICAL STRIKER
(1 cm.-kg. = 0.072 ft.-lb.)

Type of insulator	Angle of impact	Shed fractured														
		B					C					D				
		Mean fracturing energy	Number of tests	Number of insulators tested	Max. min. fracturing energy	Number of blows before fracture	Mean fracturing energy	Number of tests	Number of insulators tested	Max. min. fracturing energy	Number of blows before fracture	Mean fracturing energy	Number of tests	Number of insulators tested	Max. min. fracturing energy	Number of blows before fracture
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — —85 ↓	cm.-kg. 3.5	3	1	cm.-kg. 5.0* { 3.5* 3.0* { 9.0* 6.0* { 30.0* 21.0* 64.0† { 3.0 3.0	3 3 2 3 2 2 1 9 1 1										
		5.0	3	1												
		7.0	3	2												
		24.0	4	2												
		64.0	1	1												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +75 ↓	3.0	2	1												
		2.0	4	1	{ 2.0† 1.5† { 18.0* 12.0* { 12.0† 9.0† { 53.0† 67.7† { 10.5* 5.0*	2 1 4 2 2 1 9 4 4 3										
		15.0	3	1												
		10.0	3	1												
		49.0	4	4												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	7.1	5	2												
		3.0	2	1	{ 8.0† 6.0† 3.0† { 18.0* 9.0* { 18.0* 12.0* — { 10.5* 7.0*	6 3 4 3 1 3 2 — 2 5										
		6.8	5	4												
		12.5	12	1												
		14.75	6	1												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		9.0	6	2												
		3.6	9	2												
		11.0	8	1												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
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		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
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		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												
B.P.1 B.P.2 B.P.3 A.P.G.(A) P.G.	deg. ↑ — +55 ↓	—	—	—												
		—	—	—												
		—	—	—												
		—	—	—												

the order of fracturing energies is such that in all cases a well-aimed stone should in general strike an insulator with sufficient energy to fracture it, so that it would be misleading to compare different insulators on the basis of fracturing energies and regard must be paid to the nature of the damage.

(b) Character of Fractures.

When porcelain insulators (B.P.1, B.P.2, B.P.3, W.P.2) are hit from above, only shed B breaks. Large pieces break off the sheds, but the fracture does not spread inward from the point of contact. These insulators break more easily when hit from above, except for

spherical missile. When the energy was rather less than that required for fracture a large internal crack of the same shape as the resultant fracture appeared in most cases. On increasing the impact energy the crack spread inwards until finally the insulator fractured.

With toughened-glass types A.P.G. (A) and A.P.G. (B) (see Figs. 35 and 36) and a pointed striker there are two types of fracture. As the energy is increased from a low value a very thin slice is removed first from the surface. Further tests, not necessarily in the same place, result in a complete shattering of the insulator shed. In type B, the top shatters when shed B is hit. With



Fig. 31.—One-piece brown porcelain insulator after fracture.

insulator B.P.3. When hit from beneath, sheds B, C and D may break; with a pointed striker the edges of the sheds chip but do not break. There appears to be a band of weakness round the junction of shed C and the body of the insulator B.P.2, as this shed frequently broke off when shed B was struck. Shed B of W.P.2 is much weaker than shed B of B.P.2. With a spherical striker the shed B of insulator B.P.2 breaks up instead of the edges just chipping, the energy producing this type of fracture being the same as that required by the pointed striker just to chip the shed. Some fractures are shown in Figs. 31 and 32. With annealed-glass types B.G.2 (A) and B.G.2 (B) (see Figs. 33 and 34) large pieces break off the sheds in most cases. Sometimes a piece will fall out on the side of the shed opposite to that subjected to impact.

With both pointed and spherical strikers on pyrex glass, one-piece type P.G. (see Fig. 37), either large surface chips are obtained or pieces break off the sheds, the fracture tending to run back to parts already broken. This type of insulator is weakest when hit from on top, but its impact resistance is higher when it is hit with a

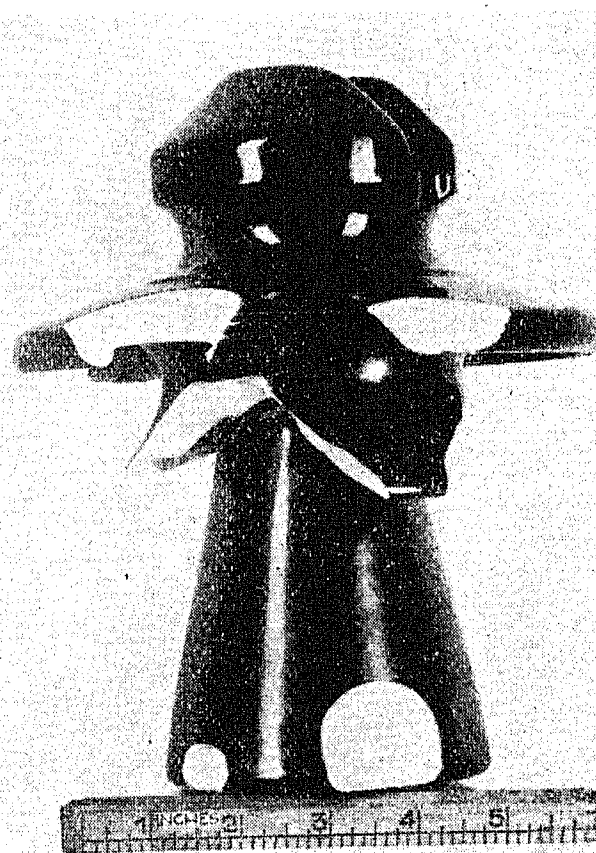


Fig. 32.—Two-piece brown porcelain insulator after fracture.

a spherical striker no surface slice is removed from the insulator before shattering occurs. The insulator will stand up to a blow of much greater energy when this striker is used.

The fragments after shattering are characteristic of toughened glass, and it was found that, in the copper-sheathed type A.P.G. (A), the glass underneath the copper sheath was covered with rectangular cracks. The top shed in each case appeared to be stronger when hit from on top.

(c) Effect of Increasing Impact Energy.

The possibility that a blow, of greater energy than that necessary just to chip a porcelain insulator, might reduce it to the same state as the glass insulators, was investigated with both spherical and pointed striker. The porcelain was subjected to impacts of energy four times as great as that required to chip it, but the only effect observed was an increase in the energy of the flying chip, with some tendency for the chip to become smaller.* Figs. 31 and 32 show the porcelain insulators after this

* This does not apply to the insulator B.P.2 when a spherical striker is used.

treatment. Figs. 33-37 show the glass insulators after fracture for purposes of comparison. In these cases the energy used was the fracturing energy.

(d) Fatigue Effect in Porcelain.

The porcelain insulators were subjected to 50 impacts of energy equal to that required to chip them. This only resulted in further slight chipping of the surface, at the point of impact, the shed of the insulator still remaining comparatively intact. Fig. 31 shows the effect of a number of blows on the insulator B.P.1. It does not seem, therefore, that repeated impacts with energies

(f) Effect of a Glancing Blow.

A few tests were made to find the energy required to break an insulator if the stone should slip on the surface of the shed. It was found possible to break pieces off the shed B of the insulator B.P.1 if the pointed striker was used so that it slipped underneath the edge of the shed, the value of the fracturing energy being about 18.0 cm.-kg. In the case of the toughened glass thin surface slices were taken off the shed, but with the present apparatus it was not possible to shatter the shed as the energy required was above the maximum obtainable. With other insulators the sharp parts of the broken edges broke the strings of the pendulum suspension and the tests were not continued. It is probable that, in practice, glancing blows would be considerably more numerous than direct blows.

(3) The Relative Security of Insulators

The destruction of the sheds of the bottle-glass and



Fig. 33.—Two-piece bottle-glass insulator, Type A, after fracture.

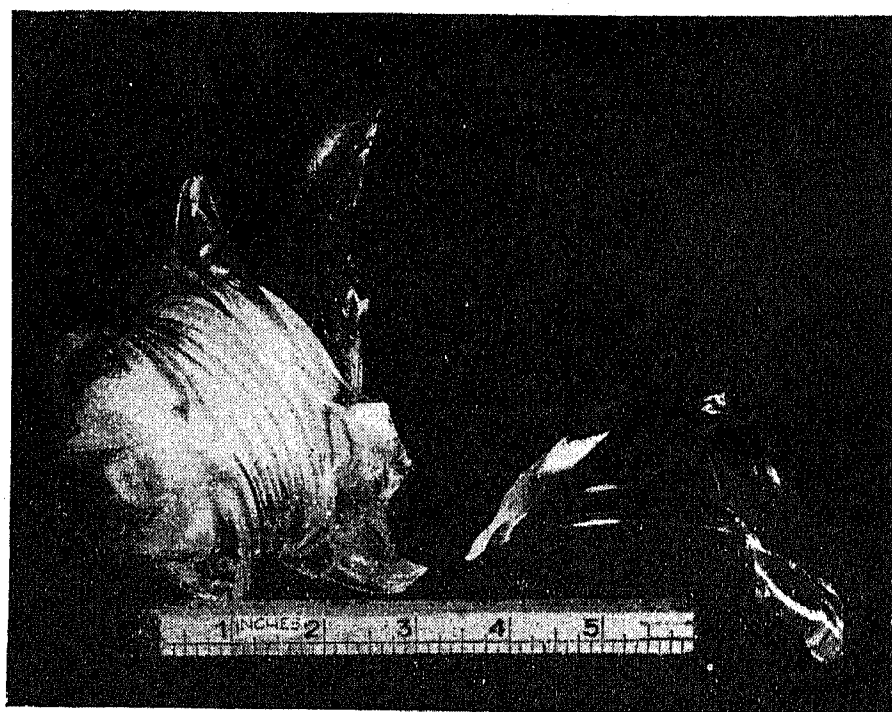


Fig. 34.—Two-piece bottle-glass insulator, Type B, after fracture.

which give a chip initially will damage porcelain insulators as much as glass insulators are damaged with one impact.

(e) Mechanical Strength of Insulators after Fracture.

The test for mechanical strength as given in B.S. No. 137 was applied to certain of the insulators after fracture. The results were as follows:—

Table 11

Type of insulator	Number tested	Load applied	Effect on insulator
B.P.2	1	lb. 1 120	No effect
P.G.	1	1 120	No effect
A.P.G. (2)	2	840 896	Top of insulator came off above the line XY in Fig. 22. The remaining parts (see Fig. 35) were shattered

pyrex-glass insulators is due to the materials breaking in tension under the action of a bending moment. The shape of the portion broken off is roughly triangular, the apex of the triangle reaching to the part *ab* as shown in Figs. 22, 23 and 24, where there is a sharp change in cross-section. The mechanism of fracture in the porcelain differed from that in the glass in the fact that the point of impact was the starting-point of the chip, while in the glass the point of impact was the mid-point of the base of the triangle mentioned. The fracture of the toughened glass can be seen in Figs. 35 and 36.

The damage done to porcelain insulators by means of a direct blow is very slight compared with the effect of impact on the glass insulators, especially in the case of toughened glass, but this conclusion does not apply in the case of a glancing blow. It has been suggested that the insulators are often fractured by lead shot. This is a case of a soft rounded missile striking the insulator at a very high speed. It is possible that the compression "skin" on the outside of the toughened

glass would render insulators made from this material very resistant to this type of impact.

It appears, therefore, that nothing very definite can

impact of a well-aimed stone will in general be much greater than the minimum fracturing energy, it would appear that a porcelain insulator hit by a stone is on the

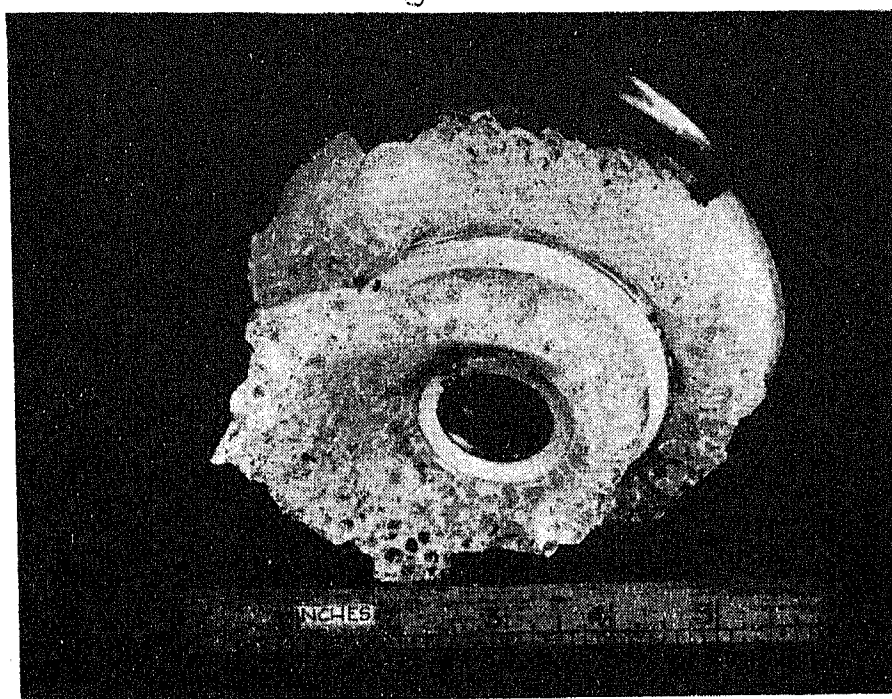


Fig. 35.—Two-piece toughened-glass insulator, Type A, after fracture.

be said about the relative impact resistances of porcelain and glass insulators under uncontrolled conditions. If smooth stones only are available the toughened-glass insulators are much more resistant to impact shocks than

whole less likely to cause a fault on account of the damage sustained than would a glass insulator. Further, from the tests with repeated blows, it also seems probable that a porcelain insulator exposed to frequent stone-

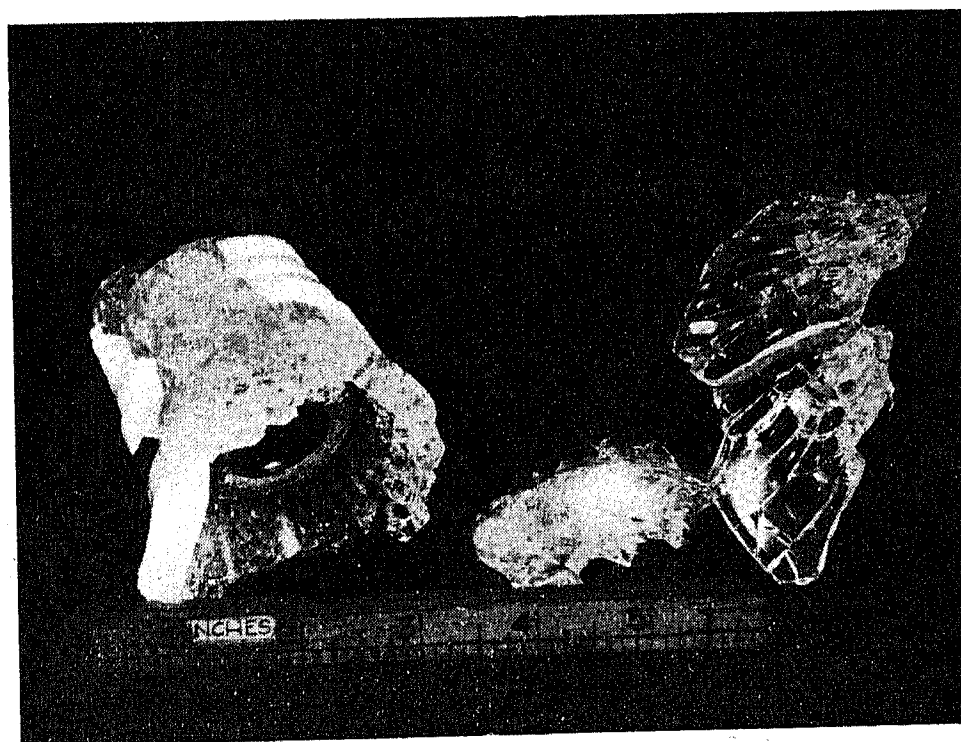


Fig. 36.—Two-piece toughened-glass insulator, Type B, after fracture.

any other type, but the damage suffered by the majority of porcelain insulators is much less. Even after fracture the porcelain and the pyrex-glass insulators will still support the maximum transverse load as specified in B.S. No. 137, but the toughened glass will only support 80 % of this load. Bearing in mind that the energy of

throwing is more likely to retain the line in service until replacement than a glass insulator exposed to similar conditions. On the other hand, it is possible that toughened glass may be more resistant to glancing blows, but this depends also on the shape of the insulator.

PART 4

IMPULSE ELECTRIC STRENGTH OF GLASS
AND PORCELAIN

The voltage for puncture through the material of an insulator must show a high factor of safety as compared

mercury electrodes were used, either flashover occurred or puncture through the thick wall of the cup at the edge of the inner electrode. The cups were successfully tested with a 5-microsecond wave in glycerine with a 2-in. sphere inside as negative electrode, the cup standing on a 9-in. metal disc having an edge radius of $1\frac{1}{2}$ in. With

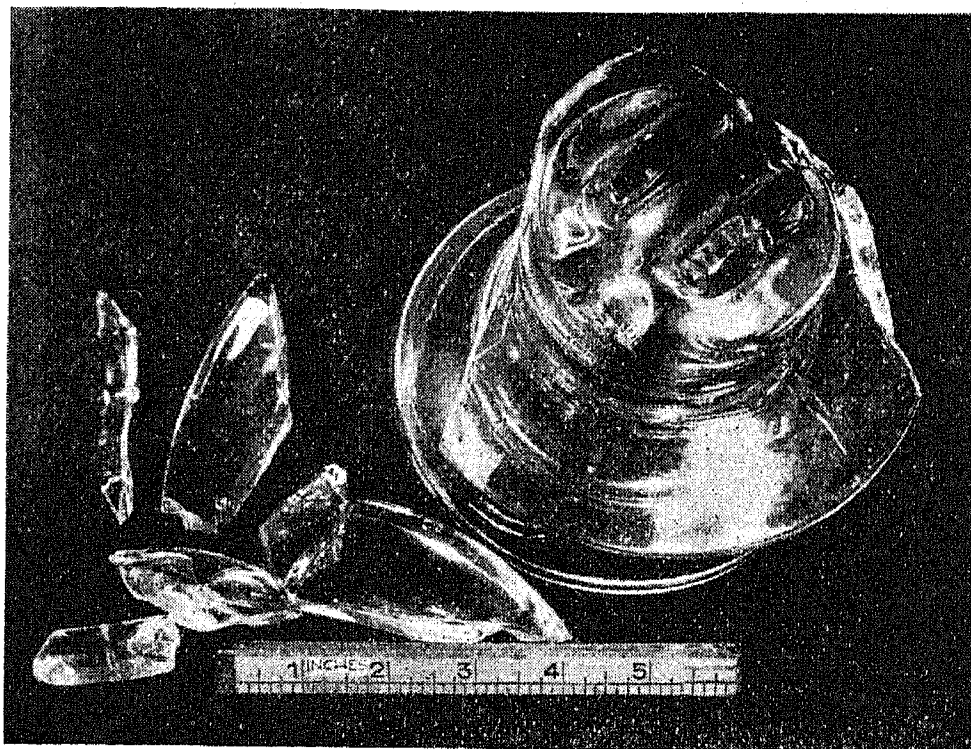


Fig. 37.—One-piece pyrex-glass insulator, after fracture.

with flashover and from this point of view the impulse electric strength of the materials is of interest. This was determined for porcelain and glass by means of the cup-shaped specimens shown in Figs. 38 and 39, according to Table 12.

Some of the porcelain cups were satisfactorily tested by coating the base and inside with aquadag and im-

a 50-microsecond wave flashover occurred over the outside of the cup.

Negative impulses were applied to the inner electrode, the outer being earthed, raising the voltage by about 5 % of the breakdown voltage at each application.

The electric strengths obtained are given in Table 13. Each figure was obtained from 6 or more

Table 12

Maker	A ₁	A ₂	B	C	D	E
Material	White porcelain, glazed and unglazed		Brown glazed porcelain	White porcelain, glazed except on bottom surface	Annealed glass and toughened glass	Pyrex
Form	$1\frac{7}{8}$ in. $2\frac{3}{8}$ in. Fig. 38 $\frac{5}{16}$ in.	$2\frac{1}{4}$ in. $3\frac{7}{8}$ in. $\frac{1}{8}$ in.	$1\frac{1}{2}$ in. 5 in. Fig. 38 $\frac{3}{8}$ in.	2 in. $3\frac{7}{8}$ in. Fig. 38 $\frac{3}{8}$ in.	Fig. 39	Fig. 39*

* Also discs 15 in. dia., 5 mm. thick.

mersing in transformer oil or glycerine. With mercury electrodes low results were obtained in oil, but correct in glycerine. The simplest satisfactory electrode arrangement was to stand the cup on an earthed plate under glycerine and insert a metal sphere 1 in. or more in diameter inside the cup, applying negative impulses to this. The cups were found satisfactory for tests with impulse waves falling to half value in 5 to 100 microseconds. In the case of the glass cups, if aquadag or

samples and is significant to about 5 %, and corrections from 5 to 15 % have been made to allow for the increase of stress over the approximate value V/d (V , breakdown voltage; d , minimum thickness) for cups of minimum thickness from 2.5 to 6 mm.

The electric strength of porcelain by all three makers is about 500 kV/cm. for a 5-microsecond wave. Glazing appears to have no effect. The strength is about 20 % lower for a 100-microsecond wave. The cup illustrated

in Fig. 38 appears satisfactory for test purposes except that the thick-walled cups should be 6 mm. thick at the base rather than 3 mm. Maker A confirmed that form A2 with a minimum thickness of 3 mm. would be considered a bad design liable to weakness in the base.

The electric strength of glass is three or four times as high as that of porcelain, being about 2 200 kV/cm. for annealed glass, and about 1 700 kV/cm. for toughened glass and pyrex glass. Pyrex glass appears very sus-

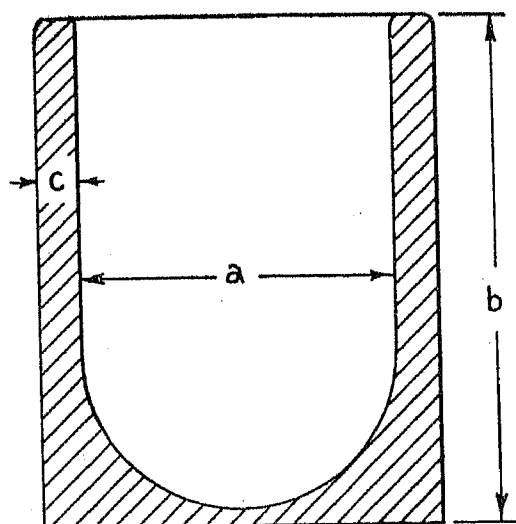


Fig. 38.—Section of porcelain cup.

ceptible to surface flaws in manufacture. Puncture of the discs occurred at such flaws (in the nature of sharp-bottomed grooves), which no doubt accounts for the low results. The figure 1 700 kV/cm. given for the cups was obtained from the six best in appearance out of 18 samples. Only one of these appeared faultless, but it gave the lowest result. The faults in the others were visible, but were not detectable by the finger nail. The worst 6 of the 18, having relatively deep flaws, gave an average strength of 600 kV/cm.

Many of the porcelain cups (especially in the second batches) also had surface depressions or excrescences. Cups with such flaws gave low results, but could be rendered satisfactory by grinding with 120 carborundum powder and water, using a rotating 2-in. sphere. The liability of different materials to possess surface irregu-

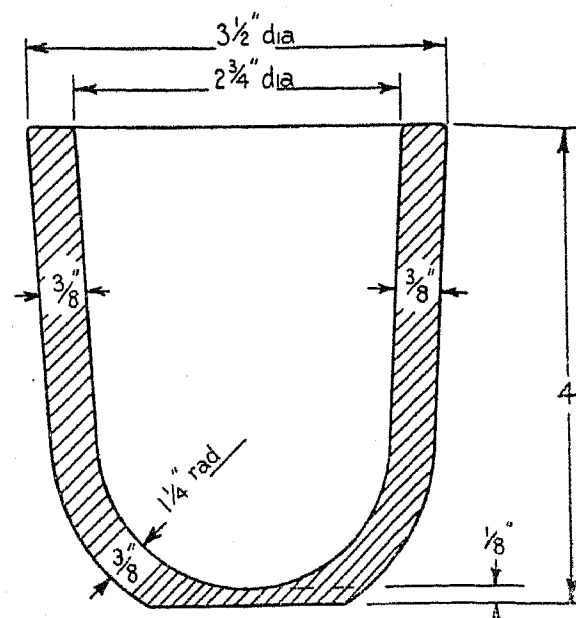


Fig. 39.—Glass cup supplied by Makers "D" and "E."

larities, and the effect of such in manufactured forms under conditions of use, appear worthy of consideration.

PART 5

THE PERFORMANCE OF GLASS INSULATORS IN HUMID AND POLLUTED ATMOSPHERES

Tests from May, 1936, to August, 1938, were carried out on two 11-unit strings of standard 10-in. diameter toughened-glass insulators, described as toughened Type

Table 13

BREAKDOWN STRESS OF PORCELAIN AND GLASS

Sample tested					Minimum thickness	Time to $\frac{1}{2}$ value of impulse wave	kV per cm.
					mm.	μ sec.	
Unglazed porcelain cups A1 (first batch)	..	..	..	..	3	5	530
Glazed porcelain cups A1 (first batch)	..	..	..	..	3	5	520
Glazed porcelain cups A2 (first batch)	..	..	..	..	3	5	480
Unglazed porcelain cups A2 (first batch)	..	..	..	..	3	5	430
Unglazed porcelain cups A2 (second batch)	..	..	..	..	6	5	530
Unglazed porcelain cups A1 (second batch)	..	..	..	..	3	5	480
Unglazed porcelain cups A1 (second batch)	..	..	..	..	3	100	400
Glazed porcelain cups B	..	..	..	..	3	5	490
Porcelain cups C (first batch), glazed inside, bottom unglazed	..	..	..	..	3	5	560
Porcelain cups C (second batch)	..	..	..	..	3	5	480
Toughened-glass cups	..	..	..	..	2.5	5	1 700
Annealed-glass cups	..	..	..	..	2.5	5	2 200
Pyrex-glass cups (selected samples)	..	..	..	..	2.5	5	1 700
Pyrex discs	..	..	..	..	5	5	950

C.P. 10.6 insulators. The insulators were tested under service conditions at the Central Electricity Board's insulator testing station at Croydon, where the conditions are exceptionally severe owing to the presence of the power-station cooling towers and the gas works.

For the winter of 1936-37, one string (Test No. B6) was erected on a test rack at ground level, and the other (Test No. A5) on the test tower. At the beginning of the winter 1937-38 string No. B6 was removed from the

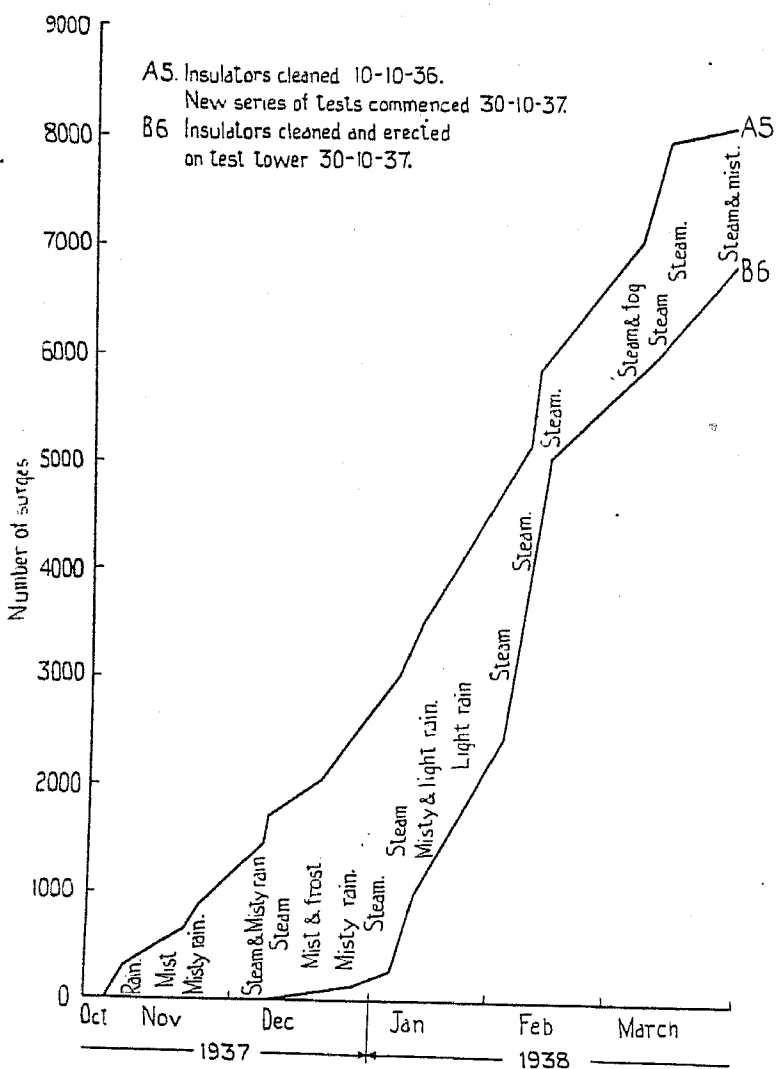


Fig. 40.—Surge counter records, toughened glass insulators. (Standard discs.)

test rack, cleaned, and erected on the test tower. Insulators No. A5 were not cleaned during the whole series of tests. The insulators were continuously energized at the maximum working voltage to earth, 85 kV, and counters were installed in order to record the leakage-current surges exceeding 20 mA. Such records appear to provide the best available measure of insulator performance. In addition, a few measurements were made of the potential distribution along the string of insulators by means of the C.E.B. live-line insulator tester.

The number of leakage-current surges recorded for both insulators for the winter of 1937-38 is shown on Fig. 40. It is interesting to note the superiority of the cleaned units B6, although this superiority is only maintained for a few months. The leakage-current surge characteristics of the glass insulators are similar to those of porcelain insulators. The performance of the glass insulators was actually found to be slightly superior

to that of the corresponding porcelain units, but it does not appear to be possible to eliminate a certain fortuitous element in such measurements, and it is not suggested that this difference is significant.

A typical potential distribution curve obtained across the string of glass insulators B6, under humid conditions, is shown on Fig. 41. It will be observed that the distribution curve is extremely irregular, the voltage drop across three of the units being negligible. Irregular potential distribution curves of this nature are also a characteristic of porcelain insulators under humid conditions, and it appears that glass and porcelain units behave similarly in this respect.

It is concluded that the performance of glass insulators in humid and polluted atmospheres is not inferior to that of porcelain units of the same shape. In general, as is to be expected, there appears to be little difference in the

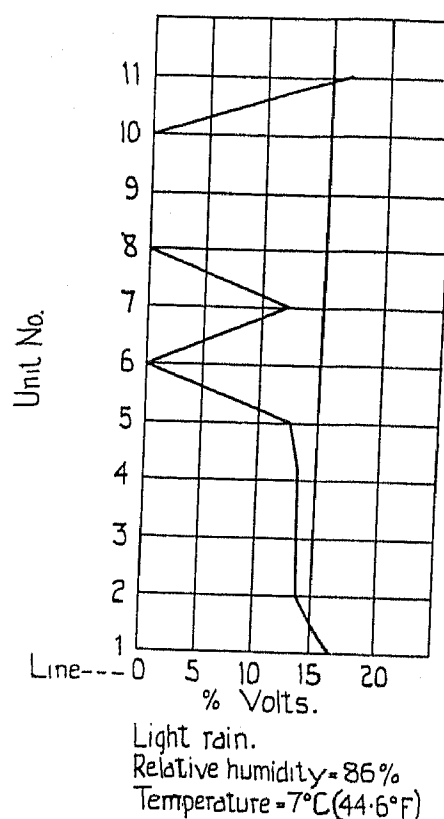


Fig. 41.—Insulator potential distribution. Toughened glass B.6 units.

surface characteristics of insulators made from glass and porcelain.

APPENDIX

THEORY OF TEMPERATURE RISE OF INSULATORS

Assume that a slab of material of thickness d with one surface blackened is exposed to radiation incident normally on this surface; then the equation for thermal equilibrium of the upper surface is—

$$W = B(T_1^4 - T_a^4) + K(T_1 - T_a)^{5/4} + (\sigma/d)(T_1 - T_2) \quad (1)$$

where

W = incident radiation intensity.

B = Stefan's constant.

K = convection constant.

σ = thermal conductivity of material.

d = thickness of slab.

T_1 = temperature of black surface (deg. abs.).
 T_2 = temperature of under surface (deg. abs.).
 T_a = surround temperature (deg. abs.).

For an artificial black body there is about 5 % reflection and a corresponding decrease in the emissivity, so that the equation becomes—

$$0.95W = 0.95B(T_1^4 - T_a^4) + K(T_1 - T_a)^{5/4} + (\sigma/d)(T_1 - T_2) \quad (2)$$

This equation may be applied to the tests on the coated

T_1 and T_2 are given by the temperatures of the thermo-junction in positions 1 and 2 or 1 and 3 respectively; T_a is the equivalent surround temperature.

The validity of the theory will be tested by the calculated value of the right-hand side of equation (2) agreeing with the left-hand side. Some uncertainty existed, however, in the correct values of σ and d to be employed owing to the presence of the cement and the fact that the thermo-junctions at positions 2 and 3 were not in all cases vertically below position 1. Reasonable allowances were made for these factors, however, and numerical calculations made as given in Table 14.

Table 14

COMPARISON OF THEORY AND EXPERIMENT FOR COATED INSULATORS

Insulators	Right-hand side of equation (2): watts dissipated by—				Left-hand side of equation (2) (theoretical watts absorbed)
	Radiation	Convection	Conduction	Total watt dissipation	
B.P.1	0.041	0.036	0.060	0.137	0.139
B.P.2	0.044	0.040	0.055	0.139	0.139
W.P.2	0.046	0.041	0.045	0.132	0.139
B.G.2 (A)	0.043	0.038	0.061	0.142	0.139
A.P.G. (A)	0.040	0.036	0.051	0.127	0.139
B.G.2 (B)	0.043	0.038	0.072	0.153	0.139
A.P.G. (B)	0.041	0.037	0.060	0.138	0.139
P.G.	0.040	0.036	0.076	0.152	0.139

Table 15

DISSIPATION OF HEAT FROM CLEAN INSULATORS

Incident radiation intensity = 0.147 watt/cm²

Insulator	Right-hand side of equation (2): watts dissipated by—			Total watt dissipation	Reflective power of surface, %
	Radiation	Convection	Conduction		
B.P.1	0.038	0.036	0.059	0.133	10
B.P.2	0.021	0.029	0.035	0.085	42
W.P.2	0.008	0.014	0.048	0.070	53
B.G.2 (A)	0.012	0.020	0.039	0.071	52
A.P.G. (A)	0.014	0.020	0.049	0.083	44

insulators by taking a small area on the top of the insulator as approximately equivalent to a small area of the infinite slab considered above and taking d as the distance to the thermo-junction directly beneath.

The numerical values of the constants are as follows:—

$$W = 0.147 \text{ watt/cm}^2$$

$$B = 5.72 \times 10^{-12}$$

$$K = 0.00027.*$$

$$\sigma = 0.0097 \text{ watt/deg. C. per cm. cube for porcelain.}$$

$$0.010 \text{ watt/deg. C. per cm. cube for glass.}$$

$$0.0113 \text{ watt/deg. C. per cm. cube for pyrex.†}$$

* From Rice's formula in the International Critical Tables.

† Data given by manufacturers.

The agreement of the right-hand side with the left-hand side of equation (2) is fairly good, and therefore it is possible to apply similar calculations to the case of the clean opaque insulators, including the glass insulators of Type A, which are provided with copper-sheathed tops. In this case R (the fraction of radiation reflected), is unknown, but is found by inserting the experimental values in equation (2) as follows:—

$$W(1 - R) = (1 - R)B(T_1^4 - T_a^4) + K(T_1 - T_a)^{5/4} + \sigma(T_1 - T_2)/d$$

i.e.—

$$R = 1 - \left[\frac{K(T_1 - T_a)^{5/4} + \sigma(T_1 - T_2)/d}{W - B(T_1^4 - T_a^4)} \right] \quad (3)$$

The values of R found from equation (3), together with the calculated watts dissipated by radiation, convection and conduction, are given in Table 15.

Table 16

PERCENTAGE OF COMPONENTS OF HEAT DISSIPATION

Insulator	Percentage of incident radiation dissipated by—			
	Reflection	Radiation	Convection	Conduction
B.P.1	10	26	24	40
B.P.2	42	14	20	24
W.P.2	53	5	9	33
B.G.2 (A) ..	52	8	14	26
A.P.G. (A) ..	44	9	14	33

The percentage dissipation of heat by the four processes has been calculated from Table 15 and is given in Table 16.

Since the temperature rises are not very large it may

be stated that roughly the percentages given in Table 16 will be the same for any lower value of incident radiation.

Similar calculations have been attempted for the clean glass insulators without copper tops, including the pyrex-glass insulators. It has not, however, been found possible to obtain very definite information owing to the additional factors involved. An appreciable fraction of the radiation transmitted through the glass without absorption is absorbed by the layer of the cement between the units, or by the metal pin in the case of the pyrex insulators, and a considerable part of this heat energy is used in heating up the adjacent parts of the insulator. This factor does not occur when the insulators have a coated or opaque surface, and therefore equation (3) will not apply. Approximate calculations show, however, that assuming a 10 % reflective power for the glasses, the heat lost by radiation and convection is about 27 % of the total incident radiation absorbed for the B.G.2 (B) and A.P.G. (B) insulators, and about 13 % for pyrex, and the remainder is dissipated by conduction from the cement to the adjacent glass and down the supports.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 10TH APRIL, 1940, ON THE PAPERS BY MR. P. M. HOGG (SEE PAGE 615) AND THE ELECTRICAL RESEARCH ASSOCIATION (SEE PAGE 625)

Mr. C. W. Marshall: I wish to begin this discussion of glass insulators by summarizing our experience with the better-known porcelain insulators. This experience was gained from more than a million suspension cap-and-pin units on 132-kV and lower-voltage transmission lines. My general finding concerning porcelain overhead-line insulators is that under the conditions encountered in this country they serve their purpose satisfactorily. Considering the specific example of the overhead-line insulator, it is found that with well-proven types the loss does not exceed 0.25 % per annum. There have, however, been one or two exceptional instances in which particular batches of insulators have failed suddenly after a few years of service, necessitating the replacement of several thousands of units. This adverse experience shows that it is essential to continue to test porcelain insulators at regular intervals until all suspect units have been eliminated and replaced. Such testing can be done conveniently with the lines in service. The test consists essentially in measuring the voltage drop across each element of each insulator string, and comparing the figures so obtained with those from a sound string. The cost of testing need not exceed a small fraction of a penny per insulator per annum, and it constitutes a valuable safeguard against failure under service conditions.

With glass insulators there is a prospect of improving on the 0.25 % per annum loss figure. The extremely uniform quality of the glass also appears to ensure that large-scale failure is unlikely. Further, the use of glass insulators would eliminate the necessity for field testing by voltage-drop methods. The various technical and economic advantages of glass insulators over porcelain insulators have caused the Central Electricity Board to experiment with glass suspension insulators on 33-kV and

132-kV lines on a limited scale. About 1 500 glass suspension units and a few cable sealing-bells of the glass types have been in use for some two years, and there has been no adverse experience whatsoever with these units. The finding from Central Electricity Board experience, which is put forward with due reservation having regard to its limitations in numbers and time, is that the glass insulator promises to become a useful adjunct to electricity supply engineering.

Mr. W. Fennell: The underlying reason for the introduction of glass insulators was that it was thought that they would prove cheaper than porcelain insulators, a very important point for those of us who are engaged in rural electrification. I therefore think that the author should have included in his paper the relative costs of glass and porcelain insulators of similar shapes and sizes. The idea was that insulators made of glass, which is ductile, could be moulded, and almost stamped, whereas porcelain has to be spun on the potter's wheel and requires a good deal of highly paid—at least, I hope it is highly paid—labour. Mass production was at the back of the minds of some of us, therefore, when we encouraged this idea. Messrs. Pilkington have now, however, gone beyond the stage of bottle glass and annealed glass and are using toughened glass, which requires, perhaps, as much labour as porcelain; at any rate it requires a great deal of control and watching, and I therefore fear that prices may not be so low in the future as they have been in the past.

I hope that a careful watch will be kept on the behaviour of the aluminous cement mentioned on page 621. I understand that it expands with age, and that its properties have been thoroughly investigated by porcelain-insulator manufacturers in the past 10 years.

Comparing the two types of insulator from our point of view, it seems that the glass insulator is superior in regard to immunity from puncturing and flashover. Apart from its greater liability to destruction at the hands of small boys, its qualities are the same as those of the porcelain insulator. Glass insulators are not conspicuous; for example, we have not as yet had any breakages on the strings of 33-kV glass insulators which we erected 3 years ago on half a dozen poles alongside a housing estate. We have, however, prosecuted one or two boys in the past for damaging insulators, and that has brought about a certain diminution of the trouble.

The question is whether one prefers to have an insulator which will crack and stay up or one which will burst and come down. It is necessary to balance these considerations very carefully for each line before making a choice between toughened-glass and porcelain insulators. If an insulator bursts it may put the line out of action at an inconvenient moment; on the other hand, if a crack develops it may take weeks to detect the faulty insulator. We had an instance of this recently when a single line, 1 mile long, supplying a works, was subject to frequent shutdowns, usually under "dew" or shower conditions. Frequent and careful inspections failed to locate the trouble. The consumer became so annoyed that he coerced us into running another line to give him an alternative supply. We eventually found that the trouble had been caused by a puncture under the conductor in the top groove of an insulator. Had this been made of toughened glass the fault would have been seen at the first inspection.

Mr. M. J. Dark: It seems that the essential difference between toughened-glass insulators and other types is the intentional production of internal stress, the surface layers being in compression and the internal layers in tension. I suspect that the difficulties of the toughening process are very great; the rapid cooling is apparently achieved by blowing air on to all the surfaces, and a certain amount of unequal cooling must be inevitable. It would be interesting to know the percentage of failures which occur during this process and also during the routine thermal-shock test at 550° C.

The insulators shown in Fig. 6 of Mr. Hogg's paper follow the design of porcelain insulators very closely—particularly Type (c), which has a shape almost identical with that of a well-known porcelain insulator. Presumably this arises from an endeavour to provide uniform thicknesses wherever possible; this, of course, is also important in the manufacture of porcelain, though perhaps not quite to the same extent. The thicknesses of the sections are similar to those adopted in the design of porcelain insulators, and I should like to know a little more about the factors governing the choice of these. In view of the high impulse puncture strength to which reference is made in the other (E.R.A.) paper one would have thought that the number of shells in, say, a 33-kV pin-type insulator could have been reduced at the expense of a slight thickening of the sheds (assuming uniformity of section to be of vital importance).

Mr. Hogg, referring to tests on pin insulators and strings of disc insulators, says on page 622: "All the insulators were subjected to 500 impulses at the maximum impulse sparkover voltage, and in every case they with-

stood the test satisfactorily." I should like to know what is meant by the word "maximum." If it means the maximum voltage which could be provided by the impulse generator, then I think that this voltage and the rate of rise should have been stated.

I see that Mr. Hogg found the tests on pin-type insulators to be rather more satisfactory than those on disc insulators. Perhaps he is referring here to tests on pin-type insulators with metal caps; I should have expected tests on insulators such as that shown in Fig. 8 to be just as unsatisfactory as those on disc-type insulators.

I should like to know how the results obtained in the extended test—in which the insulators are alternately heated by steam and cooled by artificial rainfall—compare with those of the tests in which the insulators are alternately immersed in hot and cold water with the same temperature-limits; in my experience cooling by artificial rainfall is often less severe than cooling by complete immersion.

In my opinion, laboratory tests are of secondary importance compared with actual life tests. I have heard of porcelain insulators which had given exceptionally good results on laboratory accelerated life tests, proving rather unsatisfactory in service, mainly, I think, owing to difficulties in maintaining a certain standard of excellence in bulk production; it seems probable that the manufacture of toughened-glass insulators carries with it exceptional difficulties.

Under the heading "Inspection" (page 620) Mr. Hogg states that the pieces are examined and gauged by inspectors, and that in this examination the transparency of the material is valuable, as any internal fault is easily seen. I should like to know why it is found necessary to gauge every piece, particularly those of the types shown in Fig. 6. If dimensional discrepancies are evident in the pieces does not this indicate that the stresses in the pieces themselves differ?

I note from the E.R.A. paper that during the tests to determine the ability of various insulators to withstand power arcs, final failure of certain types occurred at intervals ranging from a few seconds to 27 hours. I should like to know whether there was any visual evidence of incipient failure before the failures actually occurred. If no such evidence was present, might not failures in service occur with insulators which have had abnormally high stresses introduced during the toughening process?

Part I of the E.R.A. paper rather suggests that breakage of porcelain insulators due to power arcs is common. This, of course, is not the case.

The interesting suggestion is made that one of the toughened-glass insulators which failed during the 1 000-amp. 1-sec. test might have had an internal fault. It is also suggested that in all cases sufficient time was allowed between the tests to permit rupture of toughened glass to occur. Presumably the "sufficient time" was based on the evidence of the prior test, and I should like to know whether the authors are satisfied that a period of 27 hours or thereabouts is really sufficient.

It is stated later in the paper that glass insulators have an advantage in regard to ease of detection of damaged units; but, in view of the possible time-lag, the advantage may not be quite as great as at first sight it would appear

to be. In practice, when a multi-part porcelain insulator or a unit of a suspension or tension string is damaged by a power arc the damage is usually quite visible and, in general, the insulator can be left in commission until a suitable opportunity occurs to replace it. This, of course, does not apply with single-part pin-type insulators and single-unit tension strings, but here again there is little difficulty in determining the location of the fault, particularly with the aid of one of the excellent live-line testing appliances now available.

Turning to Part 2, I am interested to see that white-glazed porcelain insulators experience a rise of temperature slightly less than that of the glass insulators. That the rise in temperature is less for white-glazed insulators than for brown has long been known; despite this, insulators with brown glaze far outnumber those with white glaze (telegraph insulators excepted), even in countries where the temperature changes are abnormally high. This indicates that breakage of porcelain insulators due to solar radiation is not a great source of trouble.

Part 3 deals with mechanical-impact resistance, where the advantage seems to lie with porcelain insulators. I should like to know whether further tests have been made with insulators subjected to mechanical loadings and vibrations, such as are usually met with in service. I should also like to know the precise meaning of the words "maximum transverse load as specified in B.S. No. 137." Are the loads the specified maximum working loads of 400 lb. or 800 lb.; and, if so, which? Or are they the loads of 1 000 lb. or 2 000 lb. which the insulators, according to the Specification, must withstand without failure? If the figure of 80 % relates to the maximum working loads, then failure to support the line must be almost inevitable. In general, in my experience porcelain insulators which have had their sheds broken off are capable of withstanding the specified mechanical tests of $2\frac{1}{2}$ times the maximum working loads.

With regard to Part 4 of the E.R.A. paper, the results indicate a markedly higher impulse puncture strength for glass than for porcelain, but I should like to confirm that the design of the test cup, Fig. 38, with its small base thickness, would not be considered good from the porcelain-insulator manufacturers' standpoint. On the other hand, the shape of the glass test cup would appear to be very suitable for the process described in the early part of Mr. Hogg's paper.

I agree that the liability of different materials to possess irregularities, and the effect of such irregularities, are worthy of consideration; the difference between the figure of 600 kV per cm. given on page 653 for the worst six of the pyrex-glass cups and that of 1 700 kV per cm. for the best six indicates a greater divergence of results than is usual among unselected specimens of porcelain.

There is no difficulty in designing porcelain insulators which will flash-over before puncture under the steepest-fronted waves obtainable at the present time in the laboratory, and failures due solely to impulse voltage in service are almost unknown.

Mr. J. S. Forrest: In some branches of insulation technique new developments are of almost everyday occurrence, but this is not so in the case of transmission-line insulators; for example, the ordinary disc insulator has remained the same, fundamentally at least, for the

last 20 years. On this account, the development of the toughened-glass insulator is an event of primary importance. Mr. Hogg has subjected this type of insulator to comprehensive tests, and the results appear to be exceptionally satisfactory. Experience with porcelain insulators shows, however, that one can never be certain that a particular type of insulator is reliable until some thousands of units have given satisfactory service for 5 or 10 years. Perhaps glass insulators will not exhibit "ageing" troubles, but in any case the results of extensive service experience are anxiously awaited.

In addition to line insulators we have in service a few toughened-glass sealing bells, which consist of plain cylinders without any form of shedding. Using the present methods of manufacture it is not possible to make sealing bells or bushings with the conventional type of sheds. It seems, however, that insulators with corrugations rather than sheds might be produced. I should like to have Mr. Hogg's views on this question.

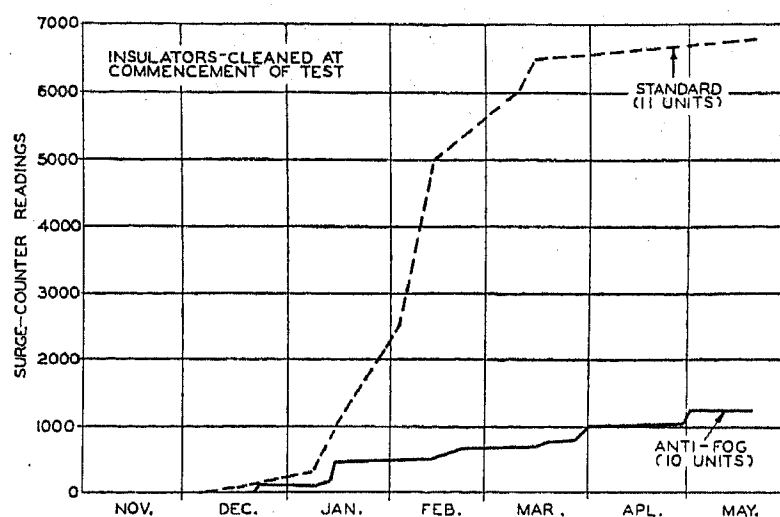


Fig. A.—Pollution tests on toughened-glass insulators.

It seems from his paper that consideration will have to be given to the drawing-up of a British Standard for the testing of glass insulators. The initial tests were based on B.S. No. 137—1930 for porcelain insulators, and this was not very satisfactory. The puncture test is difficult to apply, the temperature-cycle test might be modified with advantage, and in addition new tests should be incorporated to determine the mechanical strength of the insulator after the glass has been fractured and to check the degree of toughening by optical and mechanical means.

I should like to compliment Mr. Hogg on the nomenclature which he employs: thus a CP 10.6 F insulator means a cap-and-pin unit, 10 in. diameter, having a strength of 6 tons, and fog-type shedding. It would assist the user greatly if other manufacturers would adopt this or a similar system.

With regard to the tests to which Mr. Marshall referred, we have had some strings of toughened-glass insulators continually alive at rather more than normal working voltage since 1936. The results of some of the tests are given in Part 5 of the E.R.A. report. In addition, we have carried out tests at Croydon on the glass anti-fog unit illustrated in Fig. 6(c) of Mr. Hogg's paper. The performance of these insulators in polluted atmospheres was measured under conditions closely approximating to service conditions. The results are given in Fig. A, which

shows the number of leakage-current surges exceeding 20 mA during a period of 6 months. As a comparison, the performance of a string of standard disc-type units is shown on the same diagram by a broken line, and the anti-fog unit is seen to be a definite improvement on the standard type.

Mr. N. E. P. Harris: My remarks will be confined to Mr. Hogg's paper.

I agree that in the puncture tests the quality of oil influences the values obtained. This has been known for many years, and was discussed by Rebora* a few years ago. The British Standard† for porcelain insulators does not confine itself to the puncture test, but is based upon a sequence of tests each of which is likely to have a material effect upon the values obtained in subsequent tests.

In his description of the duration tests in progress at the present time, the author says that a mechanical test is being carried out with a length of conductor in a state of continuous vibration. I should like to know how the vibrations are generated and maintained, and the length of the conductor span. If he has been able to produce in the laboratory an accurate representation of the high-frequency low-amplitude vibrations which occur on a transmission line, he has made a valuable contribution to our knowledge of overhead-line phenomena.

Mr. H. Willott Taylor: I shall confine my remarks to Mr. Hogg's paper.

The company with which I am associated has had just over 2 500 of these toughened-glass insulators operating for periods up to $4\frac{1}{2}$ years, chiefly on 33-kV lines, and so far we have not had a single failure except on 33-kV pin-type units damaged by stone-throwing. Experience shows that 9 out of 10 shots with stones result in glancing blows, which will damage a toughened-glass insulator much less than a porcelain one. In trials I myself made I found that a blow from a stone will sometimes chip off a flake from a toughened-glass insulator without breaking it; this being so, I should like to know how deep is the surface that is in compression and that has to be penetrated before the insulator will be shattered.

A point which I feel is particularly important when lines are erected in inaccessible places is the ease with which a faulty toughened-glass insulator can be visibly detected. We spend hundreds of pounds a year on testing, using the very good testing instruments which are available now, in order to locate faulty porcelain insulators. This expenditure would appear to be quite unnecessary with toughened-glass insulators.

I should like to ask why the author uses a copper ferrule on his pin insulators. Most porcelain-insulator manufacturers use lead-alloy ferrules, and I should have thought they would be less subject to corrosion. I notice that he does not use any resilient medium such as is commonly employed when assembling porcelain insulators. Is it felt that the glass is sufficiently strong to stand any expansion of the cement which may take place?

I support Mr. Fennell's plea for details as to the price of toughened-glass insulators.

Mr. R. C. Andersen: Over a number of years various grades of glass have been tried for the manufacture of transmission-line insulators. The record in service of glass, however, has been disappointing. The papers now

presented deal with toughened-glass insulators, and because of the characteristics claimed and the test results cited in these papers, toughened glass may with advantage be investigated as a new material.

I gather from Mr. Hogg's paper that the unique characteristics of toughened glass under test derive in the main—if not exclusively—from the circumstance that a surface layer under very high compression is obtained by a specific treatment applied after the insulators have been worked and formed.

The E.R.A. test-results which constitute the second paper show that this compressed superficial layer has remarkable characteristics. Its puncture strength under a special adaptation of the B.S. puncture test is high. The insulator successfully withstands impulse tests. To thermal stressing it would seem to be impervious, and its ability to withstand controlled power arcs is approximately twice that of porcelain. No wonder Mr. Hogg is led to exclaim "long life can be anticipated."

But it was just here that I began, when studying Mr. Hogg's paper, to look for the weak link in the material chain, on the basic assumption that no material is perfect. Without physical data at my disposal I had often wondered what the coefficient of expansion of toughened glass might be. Was it much lower than the coefficient of expansion of either iron or cement? I confess I was confounded when I read that the choice of linear coefficient lay with the manufacturer, and that the linear coefficient of expansion chosen by the manufacturers of toughened-glass insulators is 8.7×10^{-6} —a highly satisfactory figure for line-insulator work. I then sought to discover why toughened-glass insulators were shattered into fragments immediately things went wrong. At best this is a very disconcerting characteristic. It indicates an inherent weakness which demands the closest investigation. After reading Mr. Hogg's paper the image of the toughened-glass insulator my mind has formed is that it is a balloon with a very thin and very taut fabric or sheath fighting valiantly to keep from exploding an internal pressure of no less than 8 000 lb. per sq. in.—to use Mr. Hogg's figure. In the E.R.A. power-arc tests, some units at least held out against explosion for 27 hours, and a number of others withstood shattering for intervals approximating 4 hours. To me the meaning of this is clear. The toughened-glass insulator is not a static but a near-dynamic entity, and time is on the side of the explosive forces. Let the compressed surface layers be overstressed by just that tiny critical amount and there is no insulator—just so much fragmentation.

I am not impressed by the suggestion that shattering is an operating asset because it eliminates live-line insulator testing to locate faulty units. The circumstance is fortuitous. I would rather have live-line testing and no dynamic phenomena. Gradual deterioration has a commercial value, even if in the nature of things the value is of a decreasing order.

But, to return to the balloon concept. Just what is the section of the fabric or sheath? How easily is it ruptured? In the answers to these questions, particularly the second, lies hidden the fulfilment or otherwise of Mr. Hogg's anticipation of long life for the toughened-glass insulator. There are signs in the paper that the superficial compressed layers are tenuous and not alto-

* *L'Elettrotecnica*, 1934, 21, p. 613.

† B.S. No. 137—1930.

gether satisfactory from the mechanical point of view. For instance, when the insulator is immersed in standard insulating oil its puncture strength is remarkably low—80 kV or thereabouts. No mention is made of what happens to an insulator when it punctures. Does it explode? The fact that with standard insulating oil the arc hugs the surface of the insulator must be given due weight in a technical analysis. Again, the pin-type insulators are fitted with copper and aluminium caps to keep the conductor more or less in position should the top shed shatter. The sensitivity of the compressed outer film is noted. Particularly is this characteristic brought out in the mechanical impact tests carried out under the direction of the E.R.A.

For many years it has been well known that the problem of line insulators is primarily a mechanical problem. Solve that and the electrical problems are then amenable to a relatively easy solution. With toughened glass regarded as a new material, it is once again necessary to recall this fact. As with porcelain insulators, the toughened-glass product stands or falls by its mechanical characteristics. The weak link is undoubtedly the mechanical efficiency of the superficially compressed layers. How long under all-weather conditions, including sand-storms, hail and the like (not to mention stone-throwing), will the tenuous band stretched taut be able to keep from exploding the pressure of 8 000 lb. per sq. in. imprisoned within each insulator? It is a question which only time will resolve and it is a question which cannot be lightly answered.

Mr. G. H. Halton: One of the most interesting observations in the E.R.A. paper concerns the long delay which occurred in certain cases between the power-arc test and the resultant shattering of the toughened-glass insulator, when that occurred. No explanation of that delay is put forward, but it seems to me that it constitutes a serious danger. For example, after a flashover has occurred on a line the circuit-breakers may be put in again, the line patrolled and the insulators reported all intact; and then, a few hours later, another interruption may occur and an insulator be found to have exploded. It is evident from the E.R.A. paper that there may be no visible sign of the damage which has taken place at the time of the flashover. This fact seems to be at variance with Mr. Hogg's statement that an insulator which is visibly whole must be mechanically and electrically sound.

The toughened-glass insulator is limited to comparatively simple shapes, and the power-arc tests were carried out on a type of insulator which has the simplest shape of all, namely the suspension insulator. It seems a pity that tests were not carried out on insulators of more complicated shape, such as the 33-kV pin insulator. It would be interesting to know what differences, if any, in the test results would have been expected had these tests been carried out on a less favourable insulator. I find it difficult to reconcile the statement in the E.R.A. paper to the effect that the mechanical strength of a toughened-glass insulator after shattering is 80 % of the maximum transverse load specified in B.S. No. 137, with the figures in Mr. Hogg's paper, which suggest a much higher figure.

The impulse puncture tests were carried out on thin and extremely simple shapes of test-piece. Could those

results be related to more complicated and thicker shapes of insulators? I should be glad to have some practical comparisons between the impulse strengths of the materials to supplement the academic figures given in the paper.

The copper or aluminium cap which is fitted as standard to toughened-glass pin insulators presents rather a problem. A power arc which is not sustained may cause no damage to the porcelain insulator, and it may still be fit for many years' service; but the copper or aluminium cap on the toughened-glass insulator must surely be damaged by a flashover. Presumably the copper will be spattered about the sheds and the insulator thereby rendered so inefficient that it has to be replaced.

Both papers, on casual reading, suggest that toughened glass is a panacea for all insulator troubles. That may be so, but from experience with porcelain insulators it is evident that short-term tests must be regarded with suspicion unless backed by satisfactory results in service over a long period.

Mr. W. Hill: I shall confine my remarks to the E.R.A. paper. First, I wish to criticize the use of the controlled arc for testing, as the conditions of such a test are not comparable with those which occur in the field. The porcelain insulator broke down so readily under this test that it appears too severe, and if this occurred in the field we should have lines breaking down to a much greater extent than actually occurs. I consider that, to get any useful data, the test should be more in accordance with what occurs in the field.

I should much prefer an insulator not to be shattered completely in the way the glass insulator suffers, but to stand up so that the line could operate for a time except under conditions of heavy rain; rather than that it should be necessary to locate a fault, and to carry out a repair immediately, having supplies off in the meantime. It seems to me that complete shattering of the insulator would lead to bigger arcing, with the result that there would be more serious conductor damage such as is frequently avoided at present.

I gather that there was some difficulty in getting glass insulators to pass the temperature-cycle test, and that they give particular trouble at low temperatures. We have sustained some very low temperatures this year, and we now know that porcelain will stand such conditions; but it appears to me doubtful whether glass would have been satisfactory in the same circumstances, particularly in view of the big internal stress. Temperatures of 0° F. were recorded, and I suggest that toughened-glass insulators should be examined at this temperature.

In the course of manufacture a good deal of ridging has been produced on the top surface of many types of glass insulators, and this coupled with slight dirt deposits has led to considerable radio interference. I should like to know whether this manufacturing difficulty has since been got over, and a perfectly smooth surface obtained.

Dr. C. H. W. Clark: I should like to ask Mr. Hogg how thick the compression skin on toughened-glass insulators is, and how resistant the glass is to abrasion. He states that these insulators will support the line even after they have been shattered; although I admit that they will stand up to a purely mechanical load after smashing, I cannot believe that they would support that

load when on the line. Surely they would immediately puncture, and a power arc would pass through them which would blow out the shattered fragments of glass. I think, therefore, that the line would almost certainly fall when an insulator was shattered in service. It is interesting to note that failure of toughened-glass insulators occurs after the power-arc test, not during it. Failure is in fact brought about by cooling, not heating. The E.R.A. paper points out that in service the cooling is likely to be much more severe; the performance of glass insulators in service is therefore not likely to be as good as would be expected from the laboratory tests.

Another criticism of the E.R.A. tests is that they seem to be too severe. An arc such as that used in the tests would probably burn through the conductor, possibly before it had time to damage the insulator. If arcing horns are provided to protect the conductor they should also prevent the arc from playing directly on to the porcelain. The E.R.A. investigators made their arc remain in contact with the porcelain for the sake of uniformity; it would seem that the power in the arc should have been less under these circumstances. In this connection it would be interesting if samples of insulators which have failed in service could be compared with those damaged by the tests.

Mr. S. M. Cox and Mr. J. Mather (*communicated*): The first part of the E.R.A. paper shows that although the complete control of the arc has greatly reduced the variability of the results, the number of pieces tested is insufficient to allow of a statistical average being arrived at. Straight-forward ultimate-strength and thermal-strength tests themselves indicate a high degree of variability, and, before comparison can be made, some indication of the standard deviation is necessary. Examination of the comparatively few results cited seems to indicate that while the difference between the glass and the porcelain is significant, the difference between the two types of glass is indicative but hardly conclusive.

A point of fundamental importance seems to be the question of the thermal and mechanical strength of an insulator after it has been subjected to one arc-over which has been sufficient to "burn" the insulator but not to

cause breakage. The importance of this point will be obvious when it is remembered that, until recently, glass manufacturers were at great pains to remove all permanent strain from glass, and it was only when pre-straining, i.e. toughening, was subjected to scientific control that it was possible to produce glass having great additional strength without the fear of spontaneous fracture. We suggest that an arc-over of the type described is very likely to convert a scientifically toughened insulator into a badly strained piece of glass. Reference to Fig. 3 in the paper by Mr. Hogg should indicate what is likely to happen. The glass surface at one point will become molten, owing to the intense heat of the arc, and the glass will naturally "flow" under the compressive force originally on the surface. The effect will be to some extent to remove the compression from the surface, so that the strain pattern will tend to heel over until the tension zone is on or near the glass surface. The presence of a tension on or near a surface is an intrinsic source of weakness and may lead to subsequent thermal or mechanical breakage under the most mild of conditions, or even to spontaneous fracture.

In the case of annealed glass, although some permanent strain may be introduced during arcing owing to the expansion, in the absence of the tension-compression pattern there will not be the same tendency for the glass to flow, or for a tension to extend to the surface.

The delayed nature of fracture, of the annealed insulators after arcing, indicates that the introduction of permanent strain is responsible for failure. Straight-forward expansion due to heating would cause immediate fracture.

It may be of interest in connection with paragraph (8) of the Conclusions, page 639, to mention that lead was used as a cement in pyrex suspension insulators, and although its shortcomings were recognized no metal was available with a sufficiently low expansion. Consequently a highly ductile metal was chosen which would allow of differential expansion, without introduction of strain under varying temperature conditions.

[The authors' replies to this discussion will be found on page 662.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT CHESTER, 18TH MARCH, 1940

Mr. G. K. Paton: Mr. Hogg shows that the type of glass now chosen for the manufacture of commercial-type insulators of toughened glass has the decided advantage of withstanding the maximum mechanical, thermal and electrical stresses which can be applied under service conditions. Glass appears to be surge-proof and is therefore eminently suitable for the manufacture of post-type insulators for high voltages.

The manufacture of commercial-type insulators requires the use of some form of cement, and an aluminous cement is mentioned as being employed without any resilient medium. It is important to know whether this cement has been proved by use in service under all weather conditions. What is the life of this cement, and what is the effect of age?

It is stated in Mr. Hogg's paper that pin-type insulators are fitted with copper or aluminium caps which support

the line mechanically in the event of the glass shed being broken or shattered. This, in effect, gives a similar design to that of the cap-and-pin insulator. The author does not give details of the manner in which the line conductor is attached to the insulator, but in practice I have found that a properly designed stirrup-type binder, which is extensively used in North Wales, has a similar effect in holding together a shattered porcelain insulator.

The mechanical test of the disc insulators is of considerable interest, particularly as it would appear that under mechanical test a modern toughened-glass insulator shows itself to be, if anything, superior to the porcelain type. This must be due in some part to the mechanical design of the fittings used so as to keep the glass under compression. The limiting factor appears to be the steel pin, and more information is desirable of the design giving these test results.

The shattering of toughened glass after it has been damaged by arcing is not necessarily a factor which should preclude the use of glass insulators. These drastic test conditions seldom occur. In view of the superior results obtained in puncture tests on glass insulators, and also the fact that with these insulators surface cracks are non-existent, it should be possible to prevent the destructive arc which alone is likely to shatter the insulator string. The present design of arcing horns in use with high-voltage transmission lines might be improved so as to avoid the effect of windage on the arc and so prevent the arc from running down the whole string.

The tests described in the E.R.A. paper should be viewed with discretion, as the conditions of test were not necessarily similar to operating conditions. The tests were made on insulators which were not under mechanical stress, and the successive application of arcs with a minimum time-period of 1 sec. is a drastic condition not likely to be met with in practice. The tests confirm, however, that the toughened-glass insulator is superior to the porcelain insulator under these test conditions.

The information given in the E.R.A. paper definitely disposes of the pyrex insulator for high-voltage work. I should be glad, however, to have some further information with regard to insulators of the bottle-glass type which are used extensively in France, possibly on lower voltages. It would be of interest to have a comparison of the qualities of bottle glass and toughened glass.

One serious defect of the glass insulator is that rupture may occur some time subsequent to damage by an arc. This is a dangerous condition for a high-voltage line, as broken glass may do considerable harm to livestock or even to human beings where a high-voltage line is erected along the verge of a main road.

The test results dealing with solar radiation are important, particularly in the case of pin-type porcelain insulators. I can confirm that repeated extremes of temperature do cause fracture and, ultimately, puncture of the insulators. Puncture due to electrical stress usually happens after slight fracture of the insulator due to expansion or contraction cracks. It is of considerable interest to know that toughened-glass insulators compare favourably with porcelain, and particularly coloured porcelain, insulators which are in use on so many transmission lines.

Damage to insulators caused by stone-throwing is not

now so prevalent, although there are a few districts where it occurs, particularly when a line has been recently erected. I should say that more damage is caused by the use of catapults.

Considerable loss and depreciation of insulators is caused during transit and in stores by the sheds of the insulators becoming chipped. This applies no doubt to both porcelain and glass insulators, but it would be of interest to know whether the effect on glass is of the same consequence as the effect on porcelain. Chipped porcelain insulators are not allowed to remain in service.

One important feature of the toughened-glass insulator is that the puncture value is 3-4 times that of porcelain. This, combined with the fact that surface cracks are non-existent with glass, should make these insulators very suitable for the building-up of post-type insulators for high voltages. In this respect our experience with porcelain insulators has not been satisfactory.

Mr. D. Williams: Advertisements of toughened glass usually show it in the form of sheets. Has the sheet to be toughened in the shape in which it is to be used, or can it be cut after it has been formed into a standard sheet? What is the effect on the glass of cutting it?

Mr. J. O. Knowles: Mr. Hogg does not explain how the glass is toughened. Presumably the shape of the glass insulator must be designed in relation to the processes of manufacture and toughening. For instance, a toughened-glass fuse bridge or arc chute might be too complicated in shape for manufacture, apart from other considerations.

Breakage of porcelain insulators through handling in stores and shops is certainly a point to be borne in mind. The proportion of the total number used may be small, but the number of breakages is worth checking.

Turning to the E.R.A. paper, I was interested in Mr. Bruce's introductory remarks regarding arc energy, particularly where the arc is uncontrolled. In an oil circuit-breaker the arc energy is produced in an oil bubble inside an enclosed tank, but an air-blown arc may not do as much damage as might be expected from its arc energy, although it is still very desirable indeed to control the arc.

Mr. H. H. Melsom: Could the long period during which the count of surges was at zero be connected in any way with the effect of weathering on the surface of the glass insulator?

THE AUTHORS' REPLIES TO THE DISCUSSIONS

Mr. P. M. Hogg (*in reply*): I am pleased to learn from Mr. Marshall that the toughened-glass insulators have given no trouble on the 132-kV lines of the Central Electricity Board, and I see no reason why they should not continue to give good service for many years.

Mr. Forrest wisely suggests that time alone can determine the reliability of these insulators, but in the meantime the results of the long-duration temperature-cycle test, started in October, 1935, are still very reassuring. I think it can be truly claimed that the design of the toughened-glass insulator is such that stresses due to expansion and contraction in any part of the insulator do not lead to the development of defects—in other words, that the insulators do not "age." Corrugated-glass

sealing bells could, no doubt, be produced, but this development must await less difficult times.

Eventually a British Standard Specification may be drawn up for glass insulators, but the Specification for porcelain insulators, with certain obvious reservations, meets the case so far as toughened-glass insulators are concerned.

Mr. Fennell raises the question of the relative prices of glass and porcelain insulators. While I think that users should obtain this information through the usual channels, it may be said that, generally speaking, the prices of toughened-glass insulators are quite competitive.

I would assure him that the performance of the aluminous cement is being carefully watched and that

after 5 years' use its behaviour is giving no cause for anxiety.

A broken single-piece pin-type toughened-glass insulator will certainly let a line down electrically in damp conditions, but the breaking of any one shed of a multi-piece pin-type insulator, or of one unit of a string of disc-type insulators, will not put a line out of commission. Further, the complete absence of the shed, or disc, due to its having shattered on breaking, renders the detection of the faulty insulator an easy matter.

In reply to Mr. Dark, the percentage of failures during manufacture and thermal-shock test at 550° C. depends on the shape of the piece and is sometimes higher than one would wish. Uniform thickness of the various pieces is very desirable, but closer regard to the properties of the material may enable a more economical design to be developed in the future.

In the maximum impulse sparkover voltage tests, the impulse generator is set to give a peak voltage which ensures sparkover on the wave front, and the "maximum impulse sparkover voltage" is the voltage at which the insulator sparks-over and not the maximum voltage provided by the impulse generator. For example, with the 33-kV pin-type insulators shown in Fig. 6(b), a 0.01- μ F impulse generator was set to give a negative impulse wave of 700 kV (peak). With this wave, which had a 0.4-microsec. wave front and a very long tail, the maximum impulse sparkover voltage was about 450 kV (peak).

I agree that laboratory tests are of limited value compared with an actual life test. The whole object of the long-duration temperature-cycle test described in the paper is to determine the life of the insulators under temperature conditions which, although not immediately destructive, are more severe than those met with in any tropical climate. As the insulators are heated by steam and cooled by artificial rain, the test is less severe than it would be if the insulators were taken through the same temperature range by alternate immersion in hot and cold water. The toughened-glass insulators still survive after nearly 5 years (over 8 500 temperature cycles).

The glass insulator pieces in question were toughened to withstand a minimum temperature-change of 110 deg. C. when cooled by complete immersion in water. They are gauged before assembly because in the course of manufacture they are handled when comparatively soft, and careless handling at this stage may deform them.

The gauging, which is of the simplest nature, is not connected with the toughening process, which is not affected by any slight deformation of the glass pieces.

In reply to Mr. Harris, the length of the conductor span in the vibration test is 29 ft., and vibration is maintained by means of a cam-operated rocking lever. The end of this lever is attached to the conductor at about the centre of the span and has a total travel of 1½ in.

No claim is made that controlled high-frequency low-amplitude vibration is generated. A very interesting study of high-frequency conductor vibration is given by Leonard C. Peskin in the *Edison Electrical Institute Bulletin* of August, 1939. In the experiments described, controlled vibration is maintained by a device which is essentially the same as a moving-coil loud-speaker.

Mr. Taylor's experience with glass insulators is encouraging. The thickness of the compression skin

depends upon the thickness of the glass pieces, and in the case of the insulator pieces is about 0.1 in.

The rounded edges of an insulator can usually be flaked without the insulator being shattered.

The question of corrosion was carefully considered before a copper ferrule was adopted on account of its excellent mechanical strength.

As galvanized tension clamps are still used with copper conductors after many years of experience, it was felt that a protected copper-zinc contact would be quite safe.

After 5 years there is no evidence of any expansion of the cement used, and there is no reason to believe that expansion will take place in the future.

I am sorry that Mr. Andersen should have been so needlessly alarmed, and I can only hope that he will read the paper again and change his conception of toughened glass. Although its application to the manufacture of insulators is comparatively recent, millions of pieces of toughened glass have been used all over the world for many years. The potential energy of the strained glass is only about 0.25 ft.-lb. per cubic inch.

Mr. Halton very properly points out that a toughened-glass insulator which was visibly whole might have a damaged strain distribution as the result of a flashover. The insulator would, of course, be sound electrically so long as it remained whole.

I would refer Dr. Clark to my replies to Mr. Fennell and Mr. Taylor, which deal with some of the points raised by him. The resistance of the glass to abrasion is not inferior to that of highly fired porcelain.

Mr. Mather refers to the possible damage to the strain distribution due to one arc-over which has not been sufficiently severe to cause breakage. Three glass disc-type insulators which had survived one application of a controlled 1 000-ampere arc for 1 second, and three insulators, which had survived a similar test at 2 000 amperes, were subsequently put through the usual temperature-cycle test, but with a temperature change of 93 deg. C. The fact that all six insulators survived this further test suggests that the damage to the strain distribution was slight and that the glass insulators were hardly converted into badly strained pieces of glass. It is true, however, that if, during the application of the arc, the glass is raised above its "strain temperature," some change of strain must take place.

Mr. Paton raises the question of the use of aluminous cement. This type of cement has been under constant observation for over 5 years, and the results of all the experiments which have been made are entirely satisfactory. These results are confirmed by the complete absence of cement trouble in service.

The high mechanical strength of the glass disc is due to the compressed surface layers, which are the unique feature of the toughened-glass insulator. Experience has shown that the loss during storage, transit and erection is very small. The development of a post-type insulator must be postponed until the end of the war.

In reply to Mr. Williams, toughened glass cannot be cut, and all machining must be done before toughening, when the glass is in an annealed state.

Mr. Knowles says that I do not explain how the glass is toughened. As stated in the paper, the process of pre-stressing, or toughening, glass consists of heating the

glass to a uniform temperature considerably above its strain temperature and then cooling it rapidly, usually by blowing air on all its surfaces, under carefully controlled conditions. The process is limited to comparatively simple shapes in which a satisfactory strain distribution can be obtained, and it is quite possible that a fuse bridge or an arc chute might be too complicated in shape for economic manufacture.

Mr. Melsom raises the question of the weathering of the surface of the glass during the leakage-current surge test, but I think that the period during which the count of surges was zero can be entirely accounted for by the comparative cleanliness of the insulators.

The British Electrical and Allied Industries Research Association (*in reply*): Much of the criticism of Part I of the paper is due to failure to appreciate the main purpose of the investigation, which was the comparison of the arc-resisting properties of the materials as such, and not the comparison between test and working conditions. The uniform conditions of the controlled arc were devised to facilitate the making of this comparison, though it was believed that they approximated to the worst conditions likely to arise in practice—for example, with a cascading arc. For this reason too, and in order to introduce as few complicating factors as possible, the comparatively simple suspension-type insulator was used. Again, no suggestion is made that breakage of porcelain insulators due to power arcs is common, as suggested by Mr. Dark, but only that breakage of toughened-glass or pyrex-glass insulators due to this cause is likely to be less common. Several speakers suggest that the tests were too severe, but this is not borne out by the results, since even at 1 000 amperes only one toughened-glass unit of the 11 tested was ruptured.

In reply to Messrs. Dark and Halton, Figs. 16 and 17 suggest that toughened-glass units which have been subjected to a power arc can be easily detected.

As regards the allowance of "sufficient time" between tests, most of the units tested at 1 000 amperes, at which current the comparison is clearest, were left for periods of the order of 6 months or a year. The majority are still available and, of these, three which survived the application of a 1 000-ampere arc for 1 sec. and three which survived the application of a 2 000-ampere arc for 1 sec. have since successfully survived a severe temperature-cycle test made up approximately as follows: (a) Three cycles, 8° C. to 64° C.; (b) three cycles, 6.5° C. to 79° C.; (c) three cycles, 3° C. to 96° C.; the time of immersion in each bath being $\frac{1}{2}$ hour.

We cannot agree with Messrs. Cox and Mather's description of the power-arc investigation. Compared with any similar investigation the results are not "comparatively few," and the results at 1 000 amperes alone establish beyond all reasonable doubt the greater arc-resisting properties of toughened glass as compared with porcelain. As regards pyrex units, conclusion (5) is sufficiently tentative.

Mr. Paton's comment on the pyrex insulator is too sweeping, as the material itself is very satisfactory and only the seal requires replacement.

In reply to the comments of Mr. Dark, Mr. Halton and Dr. Clark on the transverse-load tests, the specified

maximum working load of the insulators tested, after subjection to impact tests, was 400 lb. The results given in Table 2 were obtained by means of a wire rope attached to the neck of the insulator, and a slowly increasing load was applied by a turn-buckle and measured by a dynamometer. The results show that insulators B.P.2 and P.G. withstood a load somewhat greater than $2\frac{1}{2}$ times the specified maximum working load, whereas type A.P.G.(2) failed at lower values. Thus the porcelain and pyrex insulators withstood nearly 3 times the specified maximum working load, while the toughened glass failed at twice the latter value and therefore did not show the margin of safety required from an undamaged insulator, although still withstanding the specified maximum working load. Opinion, as stated in the paper and as evident from the discussion, is divided as to the relative advantage of the conspicuous and more complete nature of the failure of a toughened-glass insulator. Six of the 19 replies received from French supply undertakings to a questionnaire circulated by the E.R.A. in 1934 commented on the value of the easier detection of faulty glass insulators as compared with porcelain. It is only desired further to observe that the troublesome case quoted by Mr. Fennell would probably have been revealed by a test on the potential gradient, if a multi-element insulator had been employed.

In reply to Mr. Willott Taylor, Mr. Paton and Mr. Knowles, it should be remembered that the removal of a surface slice by, for example, a pointed striker weakens a toughened-glass insulator so that it will the more readily fail at a subsequent impact; but it requires quite a high energy to remove the first slice, much greater than is required for porcelain in some circumstances, e.g. with a more rounded striker. Thus, while on the one hand the greater security with glancing blows should not be emphasized, although it is probable as far as any adequate basis of comparison can be devised, yet on the other hand there is no reason to suppose that glass insulators are more likely to suffer accidental damage in transit than porcelain.

In reply to a number of speakers, the advantage of white porcelain and brown porcelain (and glass) as regards solar radiation appears to be a property of the glaze which is not necessarily related to its colour or other characteristics. There is no evidence that there is any difficulty as regards heat cycles with toughened glass; although an extension of temperature ranges on insulators might yield interesting results. Radio interference from insulators has so far not been a widespread source of trouble in this country, and there are several designs with metallized tops which have given good results on test. The electric-strength tests were made under conditions designed to give a comparison of the properties of the materials examined: to have extended such tests to other shapes and sizes would have involved determining how far design and conditions should influence the results, and one would have been led to discuss the voltage-testing of insulators, a subject which lay outside the scope of the present work. It may nevertheless be mentioned that immersion media were extensively studied, and, were it so desired, subsidiary discharges could be substantially eliminated in voltage tests on insulators.

MECHANICAL INTEGRITY IN THE DESIGN OF ELECTRICAL CIRCUIT-BREAKERS

By M. C. HUNTER.*

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SUMMARY

The paper covers some of the mechanical requirements of electrical circuit-breakers. Methods to be applied in the design stage to meet these requirements, and to guard against imperfections which may arise during manufacture, are suggested. The effects of various forms of contacts on the frictional characteristics of circuit-breakers are described, and the design steps necessary to prevent a change of friction affecting the reliable performance of circuit-breakers in service are considered.

A series of practical routine tests is put forward which should ensure that the calculated design factors are complied with, and which should also lead to an improved standard of workmanship.

Emphasis is laid on the importance of accuracy in workmanship and the necessity for careful calculations to comply with rigid standards.

The paper concludes with illustrations and information relative to suitable apparatus and shop fixtures considered essential in carrying out the prescribed routine tests.

(1) INTRODUCTION

The design and manufacture of electrical circuit-breakers cover a very wide field, and progress during the last few years has introduced so many new types, with variations of the medium in which the arc extinction takes place, such as still air, compressed air, water and oil, that all of the features described here may not be generally applicable in detail to the several groups.

It is not possible in the confines of so short a paper to go fully into all the mechanical requirements of a successful circuit-breaker, but some of the outstanding problems will be dealt with at some length.

The examples chosen more particularly relate to oil circuit-breakers of the type which normally comprises a trip-free mechanism operated by hand or power and a system of levers, generally including one or more toggles intended to adapt the short travel of the operating mechanism to the stroke of the moving contacts. The latter co-operate with fixed contacts mounted on the lower extremities of insulated bushings, the whole contact assembly being immersed in oil.

The moving contacts are mounted on some form of insulating rod which in the fully closed position is strongly biased to open by means of a spring or springs, and is accelerated when the operating mechanism is tripped free.

(2) OPERATING CONDITIONS

A general survey of the operating conditions under which switchgear has to work, shows that it is not always possible to give full maintenance to all of the circuit-breakers at regular intervals.

Long periods must elapse in many cases before it is permissible to interrupt the service, although it will be conceded that it would be most desirable to be able to open and reclose each circuit-breaker on the system at suitable periods, if only to prove that the tripping apparatus and electrical circuits are sound.

There is, however, the important question of increase of friction within the breaker itself and in the operating mechanism.

There are few published data available on this subject, but it is general knowledge that if a collection of pivots and bearings is left in a static state for any length of time the friction will most certainly increase, even if rusting of all parts is entirely prevented.

To leave a circuit-breaker in the closed position for six months without attention may not be a frequent service condition, but it is certainly not an exceptional case and must be legislated for.

The inevitable lack of regular maintenance of electrical circuit-breakers has therefore to be accepted by the switchgear manufacturers, and this condition is fully appreciated by the designers of this class of apparatus and by the industry as a whole.

(3) BASIC REQUIREMENTS OF AN ELECTRICAL CIRCUIT-BREAKER

Exhaustive investigation has been carried out since the inception of the electrical circuit-breaker to produce infallibility of operation, and more particularly to ensure that the breaker will open when required to do so, regardless of the time it may have remained in a state of rest, under load conditions, without attention.

There are many other mechanical requirements to be met such as speed of making, speed of breaking, contact pressure and correct buffering for absorption of energy at each end of the stroke, but the quality of "opening whenever called upon" is perhaps the most fundamental of all.

It is this basic problem, the solution of which is so illusive and at the same time so intensely interesting, that causes a design staff much anxiety.

There are few problems in connection with other types of machinery which present precisely the same difficulty of direct proof, in that no known test can take the place of the passage of time.

To prove the correctness of a design or even to prove the variations to an existing design (changes which may have been undertaken for an entirely different requirement) necessitates some substitute for the test of time.

A breaker may be designed, manufactured and assembled with meticulous care, and may operate successfully on all factory tests, but there is still lacking

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concrete proof that it will not stay in a closed position after long periods in service under load conditions, although the trip coil is energized, the trip latch raised and the mechanism freed.

No accelerated proving method is available which will fully replace the natural sequence of closing the breaker, leaving it on load for, say, six months and observing the result after tripping.

It is well known that in any piece of mechanism where the internal friction reduces the efficiency to a point where the output is less than half the input, i.e. to 50 % efficiency or less, the machine will not overhaul but will "stall." A typical case is a high-reduction worm gear, which may be driven from the worm end but cannot be rotated from the worm wheel.

An oil circuit-breaker with its lever mechanism, from the contacts to the trip catch, is equivalent to such a device, the breaker contacts being at one end and the trip catch at the other end of the lever train.

The arrangement of parts, accelerating springs, etc., therefore demands that there shall exist an expelling force which will at all times guarantee the opening of the contacts.

This force must be more than sufficient to overcome friction within the breaker and lift the catch and other toggle members of the operating mechanism against gravity and friction.

The determination of the required magnitude of this expelling force is not easy, and ultimately depends on the required degree of certainty with which the breaker must open under the most onerous conditions, such as inattention, rust, "glueing in" with heat, slight "freezing" of the contacts, misalignment, contact roughness due to wear, contact erosion and so forth.

The required value may be considered to be in the nature of a factor of safety to cover the changing conditions in the breaker itself. A more happy term would perhaps be "factor of assurance," and this term will be used later in the paper in connection with the breaker mechanism and the operating mechanism.

(4) CIRCUIT-BREAKER CHARACTERISTICS

The closing-force characteristic of a circuit-breaker is dependent on a variety of factors, including the particular arrangement of the components, and the materials from which they are made.

It is not unusual in oil circuit-breaker design to make the trip-free closing mechanism (hand, solenoid, spring, motor or pneumatic) a separate entity from the cross-bar lifting arrangement within the breaker itself, so that it is convenient to consider the mechanical system of the breaker as a separate piece of mechanism from the operating mechanism, with a compression or tension member between the two.

Fig. 1 shows a typical closing-force characteristic, the forces being taken on the member attached to the tension rods controlling the moving contacts. It will be seen that the force required to close the breaker increases towards the end of the stroke in a series of steps. The first slope indicates the force imposed by the dead weight of the moving parts and the gradual loading-up of the accelerating springs. At a point approximately $3\frac{1}{4}$ in. from the commencement of the stroke the contacts touch,

with the result that there is a considerable increase in the force. The final step shows the effect of an extra expelling spring which is generally necessary to ensure sufficient force to expel the moving contacts under the worst conditions of "freezing" and inattention.

(a) Contacts

Evidently a large proportion of the work required to close a circuit-breaker is accounted for by the contacts.

The form of contacts used has a considerable bearing on the expelling force of that breaker. Some contacts are 100 % expelling, for instance the spring-loaded butt types, whereas others of the sleeve type are 100 % holding and require a force of the same magnitude to withdraw as to close.

Further, on short-circuit, the members of some forms of contacts may be drawn together, so adding to the load and leading to a substantial increase in the total friction.

A change in form or in the number of contacts for different ampere ratings will alter the whole characteristic

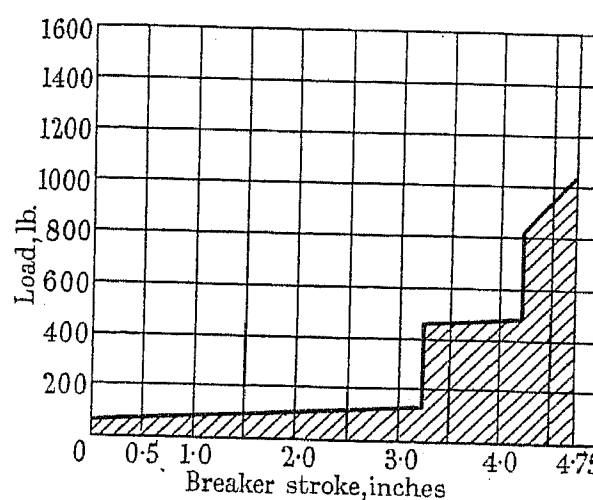


Fig. 1.—Closing-force characteristic of a typical breaker. Loads taken on the stroke of the breaker.

of a breaker. For this reason it is strongly recommended that a routine test be carried out on each and every breaker.

Figs. 2, 3, 4 and 5 show the frictional characteristics of several forms of contacts. Taking a typical finger contact, it will be seen from Fig. 2 that the force to close against one single finger, in the case of silver surfaces, changes from 0 to 21 lb. over the travel, and for hard copper from 0 to 13 lb. This difference in the coefficient of friction between copper and copper, and silver and silver, is most pronounced, and a change from one metal to the other might make all the difference between a satisfactory and an unsatisfactory breaker. This type of finger has a small self-expelling force of 2.5 lb. initially, falling to zero over its travel.

It is important to realize that the condition of a silver surface, particularly that produced by electro-plating, can by a process of burnishing be modified to such an extent that the coefficient of friction is reduced by 3 to 1. The process consists of rubbing the contact surfaces to and fro on a highly polished, hardened steel plate. When two "electro-silvered" surfaces co-operate with a sliding motion it is almost essential to burnish one of the mating surfaces, or actual seizure may take place at quite moderate loads.

The arcing contact (Fig. 3) has no expelling force for the first $\frac{7}{8}$ in. of its opening travel, and actually requires a reverse force of $3\frac{1}{2}$ lb. to withdraw, although the closing force over the same part of the travel is $3\frac{1}{2}$ lb. Figs. 4 and 5 show further variations.

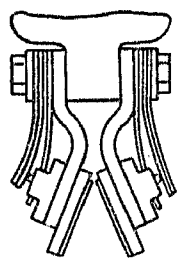
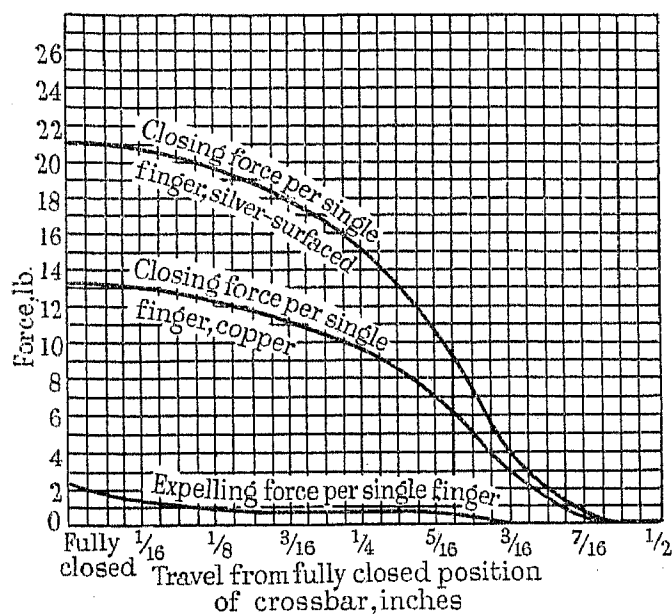


Fig. 2.—Load characteristics of 45° type main finger contacts.

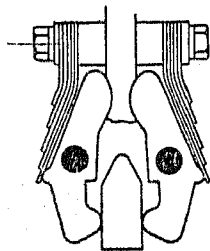
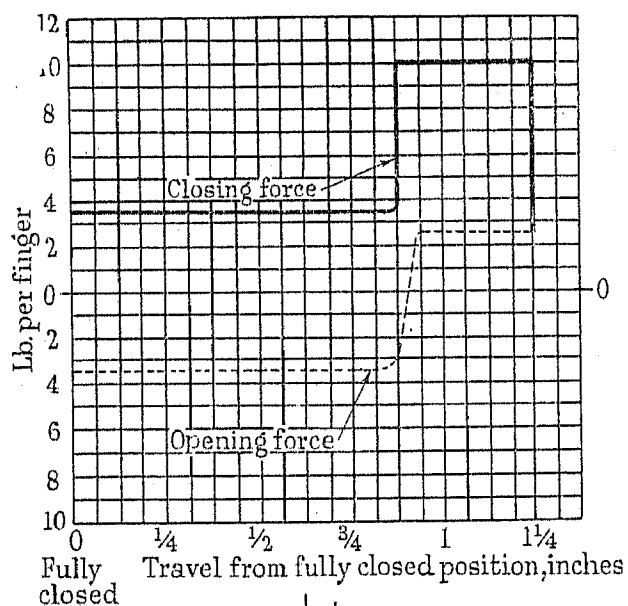


Fig. 3.—Load characteristics of high-pressure arcing contacts.

The contact shown in Fig. 5 is inherently a form with no expelling force and requires a reverse force to withdraw, over practically the whole travel.

Judging by the many diverse forms of contacts in use,

no design of a circuit-breaker can be commenced without full data of the contact characteristics.

(b) Mass of Moving Parts

From a study of Fig. 1 the dead weight of the moving

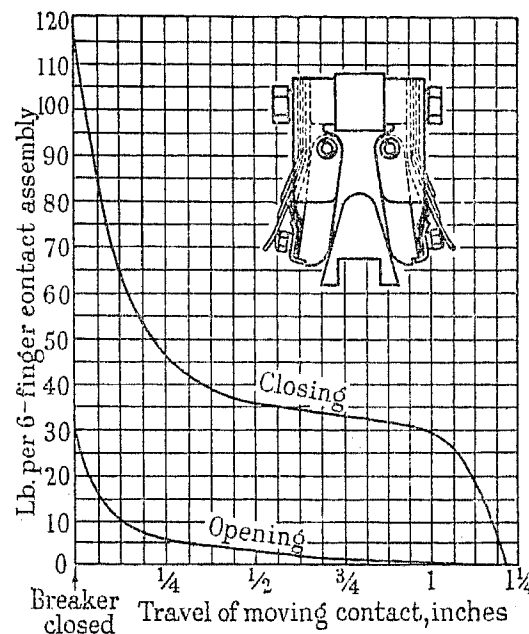


Fig. 4.—Load characteristics of pivoted-type arcing contacts.

parts does not appear to be of great importance, but on taking into consideration the energy $Wv^2/(2g)$ which has to be put into them and absorbed at the end of the stroke it is seen that the dead weight must be kept to the absolute minimum.

(c) Accelerating Springs

The forces from the accelerating springs are of considerable magnitude, and it may be asked why accelerating springs should not be provided on such a generous scale that under no circumstances could the breaker hold in

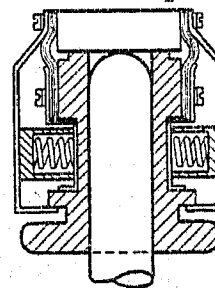
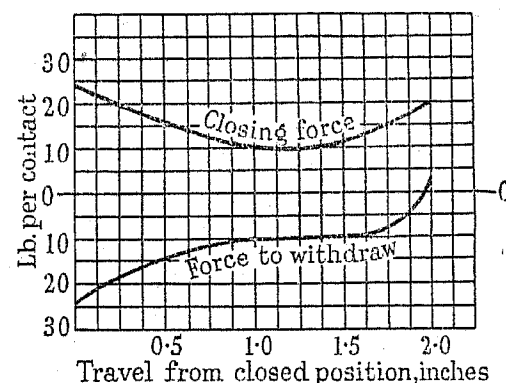


Fig. 5.—Load characteristics of sleeve-type contacts.

when tripped. The answer is provided by a consideration of economic factors. Extra accelerating springs mean increased loads on the parts, leading to additional stresses and in turn larger-diameter pins, greater friction radii,

heavier moving parts, more massive overshoot devices, etc., resulting in high-power dashpots in order to deal with the increase in energy at the end of the opening stroke. These are real problems, and it can be said that when the primary forces to close the contacts, and the required expelling forces, are established, the basic cost of the mechanical parts of the breaker is more or less fixed and the order of size of the operating mechanism is determined.

(d) Short-Circuit Forces

Short-circuit forces have a bearing on the matter, but short-circuits of maximum rating are a very rare occurrence in the life of a breaker, and because these forces are not repeating the parts may be stressed in design very highly, on the basis that the loads are transient and not of a fatiguing nature.

In many cases the resulting forces do not produce stresses which are limiting, but if they are excessive an alternative to avoid legislating for the stresses which are imposed so infrequently is to pre-trip the breaker with some momentum device or its equivalent.

It is suggested that where the extra energy required to close against the short-circuit amounts to more than 20 % of the no-load closing energy of the breaker, a momentum trip device or its equivalent is the economic solution.

(e) Friction of Fulcrum Pins, etc.

The friction due to fulcrum pins, bearings and guides is in the order of 10 to 20 % of the total force required to close a breaker, depending very largely upon the diameters, all of which must be kept as small as possible consistent with correct design stresses for the material used. A value of the coefficient of friction for the fulcrum pins in the mechanism must be assessed. It is sound practice to use a non-rusting material such as ground stainless steel for all pivot pins, and the author has established that for this material a coefficient of friction of 0.1 is a suitable figure for circuit-breaker calculations when the parts are moving, and of 0.25 when the parts are static.

(5) CO-ORDINATION IN DESIGN

From the foregoing it is evident that contact friction and mass of moving parts are the two most serious mechanical factors in the design, but all of the components must be taken into consideration. A rational sequence in which the design studies might proceed is as follows:—

(i) Decide upon the type of contacts to be incorporated in the design of the breaker, and establish with some precision, by actual test or calculation, the required force to close the contacts and likewise establish the inherent expelling force, if any, or the negative characteristic.

(ii) The weight of the co-operating contact bar, the tension rod with fixings, the crosshead and other primary moving parts must then be evaluated after first stressing to withstand the forces imposed by (i).

(iii) The accelerating springs must be designed to move the total weight as evaluated under (ii) at the required opening speed when the contacts part, and to provide a sufficient force to overcome the friction of all the moving pins under their known loads.

It is usual to allow the accelerating springs to act throughout the whole range of the stroke, finishing "free" at the end of their travel.

(iv) The bearing areas and bending moments of all pins and levers should then be checked to suit the loads imposed by (i), (ii) and (iii). A separate check should be made to cover the maximum short-circuit forces, unless a pre-tripping device is incorporated in the design of the operating unit. Some rechecking of weights may be necessary at this stage.

(v) An evaluation should be made of the amount of work in foot-pounds required to perform the closing operation at the specified speed, including all friction and short-circuit forces as may be necessary.

(vi) The overshoot stop for the absorption of the remaining energy in the moving parts at the end of the "closing" stroke must be designed on a rigorous basis.

Should a power-operated mechanism be fitted, the remaining energy, when operating, say, on high voltage, may be a serious matter and a solid overshoot stop quite inadmissible. If a spring stop is fitted, the energy will be absorbed in a given travel and then returned to the moving parts and so on until dissipated in oil swash and continued bounce. The overshoot travel may be disastrous to the breaker contacts and for this reason must be kept down to a minimum.

The absorption of the excess energy by means of springs has therefore distinct limitations. For heavy moving parts, resort must be had to oil dashpots.

An oil dashpot can be designed to dissipate completely a large amount of energy in a short stroke. Moreover there is no return of energy to the moving parts.

(vii) The energy remaining at the end of the "opening" stroke must be absorbed in a similar manner, and the oil dashpot has to be calculated to bring the moving parts to rest with no residual energy. In this connection in oil circuit-breakers, dashpots for the opening stroke are conveniently flooded, but to cover conditions of operation when the oil tank is removed some form of spring buffer should be incorporated. In these circumstances bounce is not important.

(viii) The force closing characteristic over the complete stroke of the circuit-breaker, including weights, friction, contacts, short-circuit forces and springs can now be plotted, and the maximum force at the fully closed position definitely ascertained.

(ix) The final step is to calculate the expelling force on the contact bar in the closed position; the ratio of closing force to expelling force is thereby determined. If the resulting ratio is not satisfactory, a quick-acting spring of sufficient strength to correct the ratio should be incorporated in the design.

Referring again to Fig. 1, a typical diagram in accordance with conditions specified under (viii), the area shown hatched gives the total work in inch-pounds, and the ordinates indicate the load on the contact bar at varying points on the stroke of the breaker.

By the introduction of levers or toggles in the internal mechanism of the breaker, the forces are modified and the travel is consequently modified to some shorter and more convenient stroke to suit the selected operating mechanism.

The closing characteristic as viewed from the operating

mechanism is substantially changed; every endeavour should be made in designing the system of levers in the breaker to reduce any peaks. The "peak" load is the governing force for which the operating mechanism has

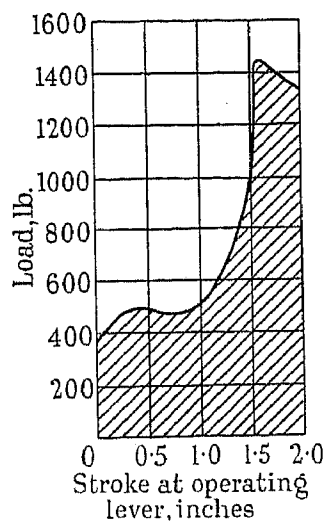


Fig. 6.—Closing-force characteristics of a typical breaker with loads taken at point of application of the mechanism.

to be stressed, so that it is essential to keep this "peak" down to a minimum. Fig. 6 represents the new order of things, from which it will be gathered that the force to pick up the breaker parts is 400 lb., the maximum force to close at the end of the travel 1 350 lb., and the peak load 1 450 lb.

The area shown hatched in Fig. 6 will be substantially

the same as that given in Fig. 1. If friction is included for each pin, however, then the area will be somewhat greater.

(6) OPERATING-MECHANISM CHARACTERISTICS

This brings us to the other side of the natural dividing line in the apparatus. The perfect mechanism, operated by solenoid, compressed air, spring or other medium, should theoretically have a characteristic to correspond to the required input of the breaker, plus the energy required to accelerate the moving parts at the specified closing speed.

This desirable line-up is seldom attainable in practice, but some matching is of importance and one point is vital, namely that the force available from the operating mechanism at the commencement of the stroke must be in excess of the force required to lift the moving parts of the breaker. Thereafter, momentum will smooth out the differences, provided the disparity between the two characteristics is not too great.

The primary forces from the diverse types of power-operated mechanisms in common use differ radically from each other, as will be seen in Fig. 7, and this calls for some comment. In the case of the solenoid the pick-up force is relatively small, due to the large air-gap when the pole-piece and plunger are widest apart. It is also gradual in pick-up, owing to the time taken to build up the flux. In many ways this is ideal.

Exactly the reverse is the case with a loaded spring,

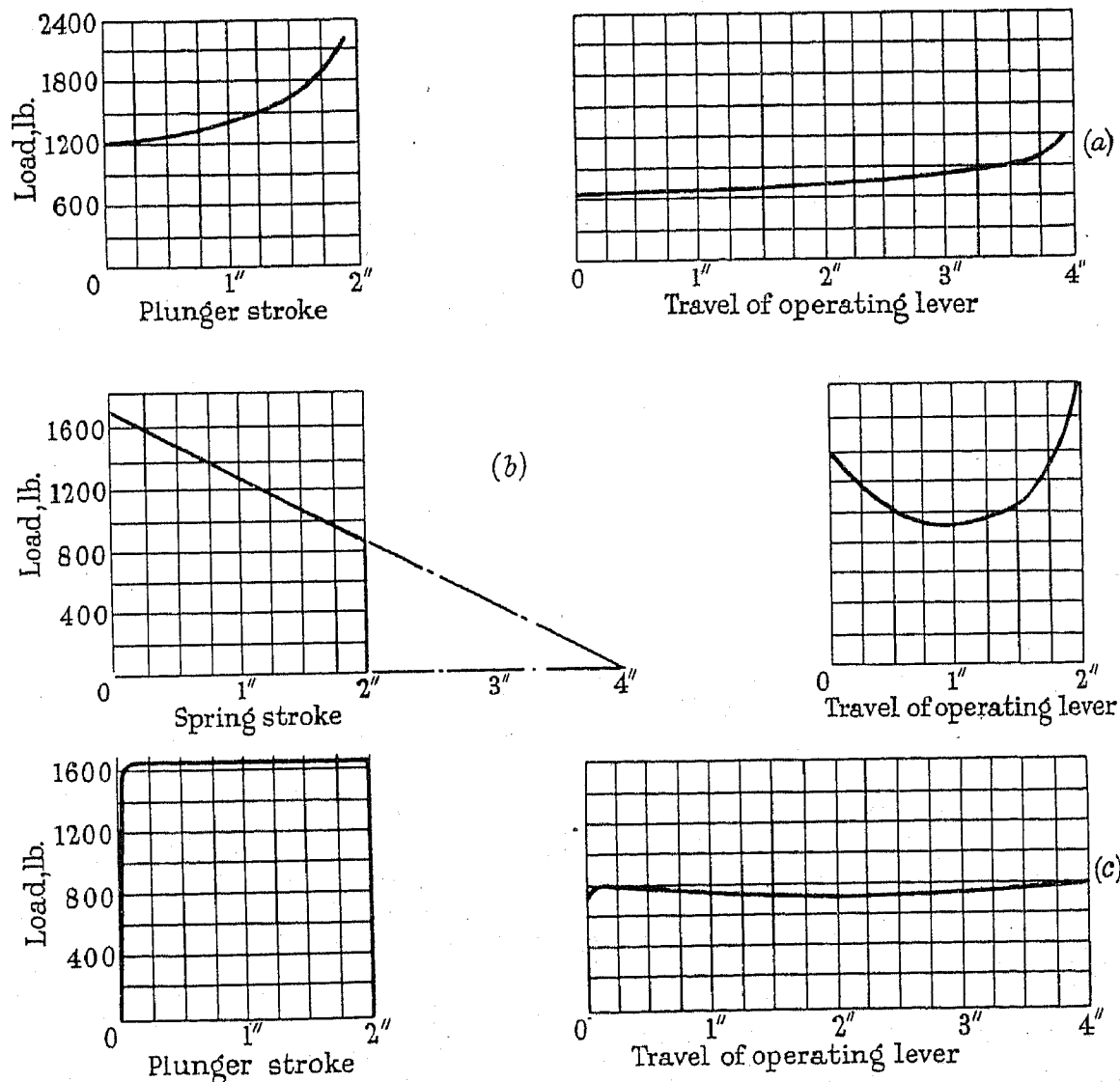


Fig. 7.—Primary forces from various power-operated mechanisms.

(a) Solenoid. (b) Spring. (c) Pneumatic.

which is most powerful at the instant of release and with which, except for its own mass, the speed would be infinite when taking up the slack in linkage, etc. This adverse factor must be taken care of in the detail design of the operating mechanism.

The compressed-air operating mechanism gives an approximately constant force from one end of the stroke to the other, provided the operating valve is fully opened throughout the stroke. This involves stressing for a greater force at the commencement of the stroke than would be necessary, for example, with a solenoid.

It is quite evident from the above that some modifications to the basic characteristics are necessary before the force is passed on to the breaker, and more particularly in the case of spring-power mechanisms.

It is not unusual to introduce some form of toggle in the operating mechanism itself to adjust this disparity and to reduce the tripping impulse to a reasonable level.

These various arrangements of parts result in considerable friction, and no matter what type of operating mechanism is selected each and all are common in one respect—that is, a reverse force is required from the breaker to cause the levers, toggles and catch to move when the latch or prop is released by the trip circuit.

If there is any undue binding or tendency to stick in the system of parts, it is possible that the reverse force from the breaker may be insufficient to ensure the desired result, and a suitable margin must be provided.

(7) MECHANICAL FACTORS OF ASSURANCE

While disclaiming any intention of attempting to lay down final factors of assurance for all classes of circuit-breakers and for operating mechanisms, there is need for a general recognition that no serious mechanical design can be attempted until factors of assurance have been decided.

(a) Breaker Mechanism

It has been pointed out that the breaker mechanism must provide a suitable expelling force, and that the "factor of assurance" for the breaker may be expressed as a ratio between the closing force and expelling force at the operating member.

Fig. 8 shows an elementary picture of a set of changing mechanical conditions in a circuit-breaker, the closing and expelling forces varying with increases in friction.

The graph assumes a breaker requiring a force of 1 000 lb. at the point of application of the operating mechanism and providing an expelling force of 250 lb., i.e. 0.25 of the closing force. The friction in the breaker, including contacts, in this case, therefore accounts for 750 lb. of the closing force.

If the friction conditions were to change for the worse the closing force would increase and the expelling force would decrease until a point would be reached where the breaker would fail to open. This diagram emphasizes the critical part which friction plays in the design of a breaker, and the essential need for a factor of assurance. It shows that an increase of 33 % in the friction, say from a coefficient of 0.22 to one of 0.30, would cause the breaker to stick in. The factor of assurance of 4 is not an unusual one, but the author's experience indicates that it is a minimum, and that although there are many types

of breakers which are greatly superior in this respect the importance of designing to calculated minimum margins cannot be over-emphasized.

The checking of these forces is a simple matter on any type of standard breaker. A practical method of carrying out the operation is described later, and this forms a most enlightening routine test, disclosing imperfections in design, workmanship and alignment which can be found by no other means.

To "design" to a suitable factor is not simple and is in fact rather tedious, but it is possible and is carried out in regular practice.

Of course, no design by rigid calculations can be successful without an established standard of workman-

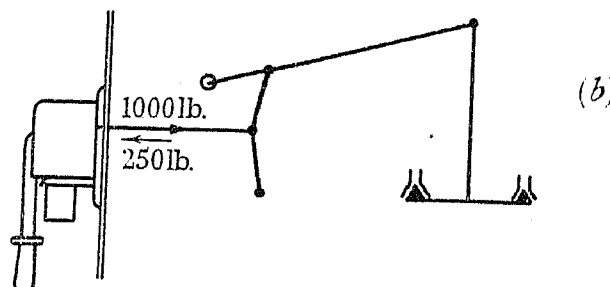
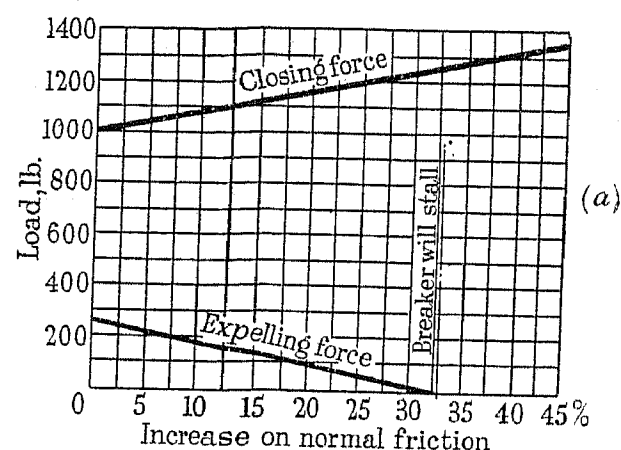


Fig. 8.—Effect of increase in friction, on closing and expelling forces. Normal breaker requiring 1 000 lb. to close and giving 250 lb. expelling force in fully closed position.

ship, which may vary in different factories. Misalignment can negate the most careful design, and the point must be stressed that workmanship and design go hand in hand. In fact, it can be said that it is impossible to carry out the design calculations for a successful product without a knowledge of the traditions and standard of workmanship of the factory which is to carry out the work.

(b) Operating Mechanism

There arises another question of major importance. What should be the margin between the expelling force of the breaker and the force required to cause the trip-free parts of the operating mechanism to move against friction and gravity?

The pins and levers which go to make up an operating mechanism will most certainly tend to adhere to each other if left under a load for some considerable time. Any lubricant which may originally have been between the surfaces will be squeezed out, and the residue will probably oxidize or solidify.

On the assumption that a test load is applied to an operating mechanism before leaving the factory, it is

reasonable to suppose that the observed value will bear no close comparison with the force required after the inevitable period of rest. Experience would indicate that the coefficient of friction could not possibly increase by more than, say, 300 %.

The conclusion is therefore reached that when measured in the factory the force required to break up the operating mechanism when tripped in the factory should not be more than one-third of the expelling force from the breaker.

The break-up force of an operating mechanism can be found by calculation, but it is rather a lengthy and troublesome study, and the actual load is best established by practical tests on several production units.

When the figure has once been established, the information should be recorded on the manufacturing drawings as a passing figure for the factory and as a guide to the designer for all time.

There is seldom any difficulty in meeting this design factor of assurance of 3 to 1, and in practice 5 and even 10 to 1 is not unusual. Nevertheless, vigilance is required to ensure that in production each and every operating mechanism meets the established figure, otherwise the whole basis of the design is nullified.

(8) FACTORY TESTS

From the foregoing it will be gathered that, having legislated for definite "factors of assurance" in the design of a breaker and in the applications of the operating mechanism, it is an absolute necessity that these factors of assurance should be verified on production, not only as type tests, but as routine tests on every unit, both breaker and operating mechanism.

The method adopted in the case of a breaker is to apply a simple lever of known mechanical advantage to the point at which the operating mechanism is usually attached and, by means of a spring balance on the end of the lever, to ascertain the force required to bring the contacts into the fully closed position. The load is held for some seconds and then released very slowly. If the spring balance is watched carefully during the release of the load, the pointer will be observed to give a decided snatch at some considerably lower load than that required to close. The reading of the spring balance at the point of snatch is the expelling force of the breaker and is an indication of when the contacts first release their grip. The ratio of the closing load to the expelling load so ascertained is consequently a measure of the factor of assurance in the breaker unit. It is good practice to record the closing and expelling force of each breaker on its serial card, so that, in the event of any trouble occurring in the field, records can readily be referred to.

The test required for the operating mechanism is somewhat different. The mechanism, separated from the breaker, is latched in the closed position, and a load is applied to the output lever in graduated steps, the trip bridge being lifted at each step to find the load at which the mechanism definitely breaks up.

Having once established a good average figure, a constant dead weight or spring load of similar value may be used. The routine test then resolves itself into loading and tripping, say 4 times, a matter of only a few minutes.

It is a matter of importance that this test be carried out dry, i.e. devoid of any lubricant on the pins or links, as this gives the most onerous condition.

(a) Testing Fixture for Breakers

For checking the closing and expelling forces of small breakers in large quantities, it is almost a necessity for production reasons that the test should be applicable with the breaker unit and operating mechanism assembled together. This necessitates applying a load to the breaker without passing the force, with consequent friction, through the operating-mechanism toggles.

Fig. 9 shows the mechanical details of this device. In practice the cover is removed from the hand operating mechanism, and the ball-bearing fulcrum for the test lever is fixed to the frame by bolts. A nose at the bottom end of the lever is arranged to press directly on to the push rod of the breaker, and an indication pointer is

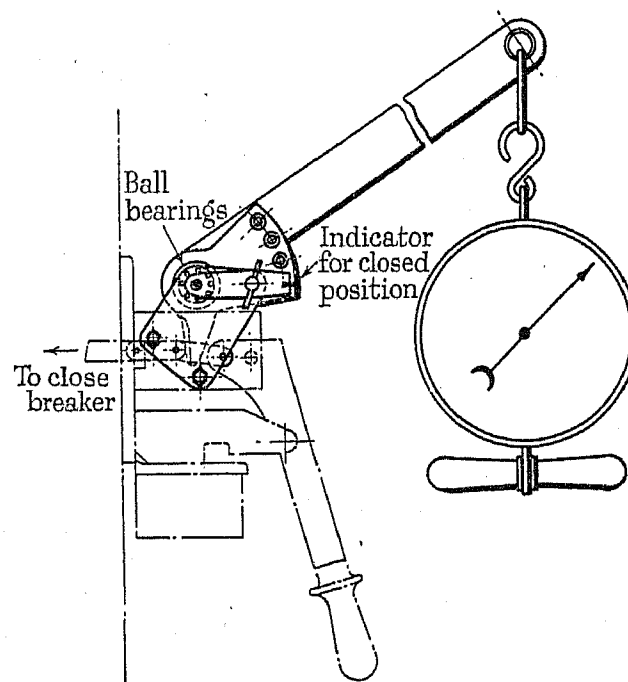


Fig. 9.—Testing fixture for breakers with operating mechanism in position.

provided to ensure that the breaker is brought to the fully closed position before reading the closing force on the spring balance. The expelling force, as described previously, is read on the first snatch of the pointer, during the time that the load is released slowly.

Fig. 10 shows the details of a much heavier device suitable for applying to larger breakers where the forces involved require the use of pulley blocks. In this case the operating mechanism is entirely removed and is replaced by a vertical stand incorporating the necessary lever. In all the above fixtures the mechanical advantage of the lever is marked on a plate, together with a correction constant for the weight of the lever itself.

(b) Testing Fixture for Operating Mechanism

For carrying out a routine break-up test on small hand-closing operating mechanisms it is most convenient to have a fixture with a standard dead-weight which is lifted when the mechanism is closed. Details of such a device are shown in Fig. 11. The dead-weight is lifted just clear of the stand by a plain bell-crank mounted on ball-bearings and located within the fixture. A square

cover-plate at the top of the frame indicates the position of the fulcrum of the bell-crank.

This fixture also makes provision for submitting the

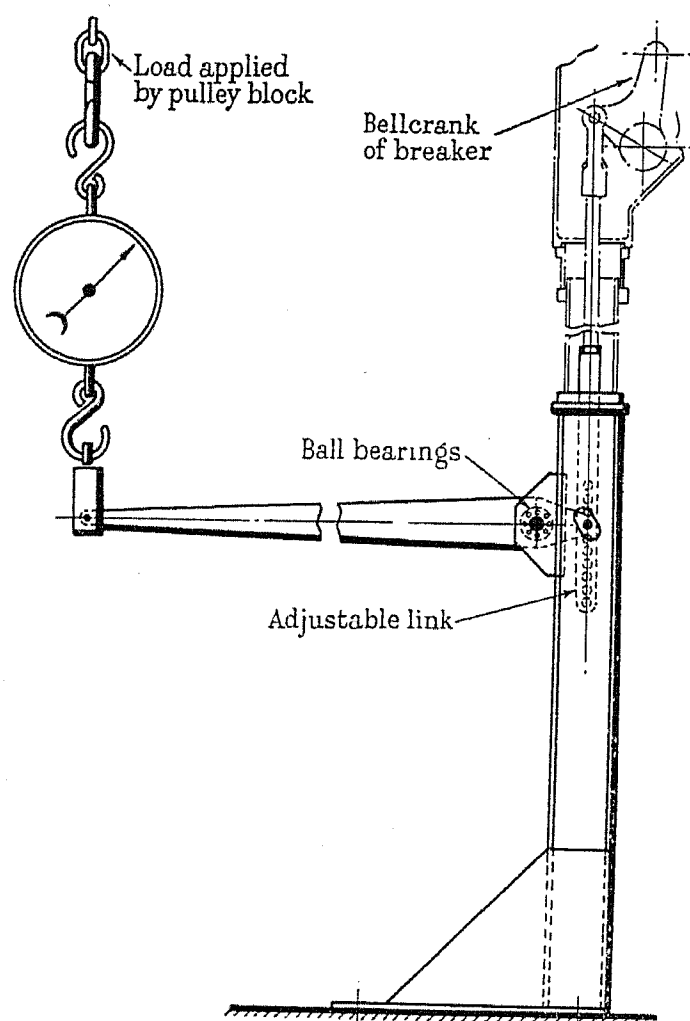


Fig. 10.—Testing fixture for breakers with operating mechanism removed.

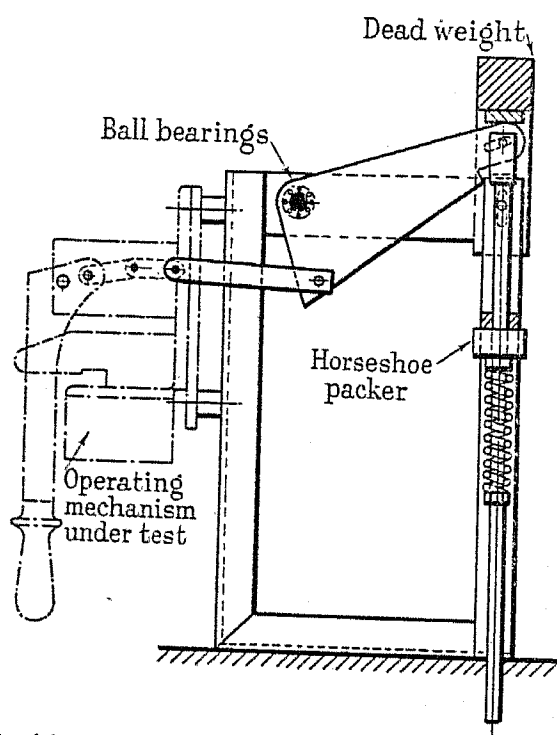


Fig. 11.—Testing fixture for small hand-operated mechanism.

mechanism to a full-load test. There is a spring within the frame at the right-hand corner, and, when the handle is closed, the vertical rod inside the spring draws it up to the full stroke but without compressing it.

When it is desired to impose a load on the mechanism, in addition to the dead break-up load, one or more horseshoe packers is placed on the top of the spring. The mechanism is operated and the spring is compressed to the extent of the packer or packers, each packer producing a known unit load on the mechanism.

When the mechanism is fully loaded in such a manner the electrical tripping values can be readily checked.

Fig. 12 represents a stand fixture for testing the break-up force of larger power-operated mechanisms, e.g. solenoids. It is designed for universal application. Each side will take various adaptor plates, one side being:

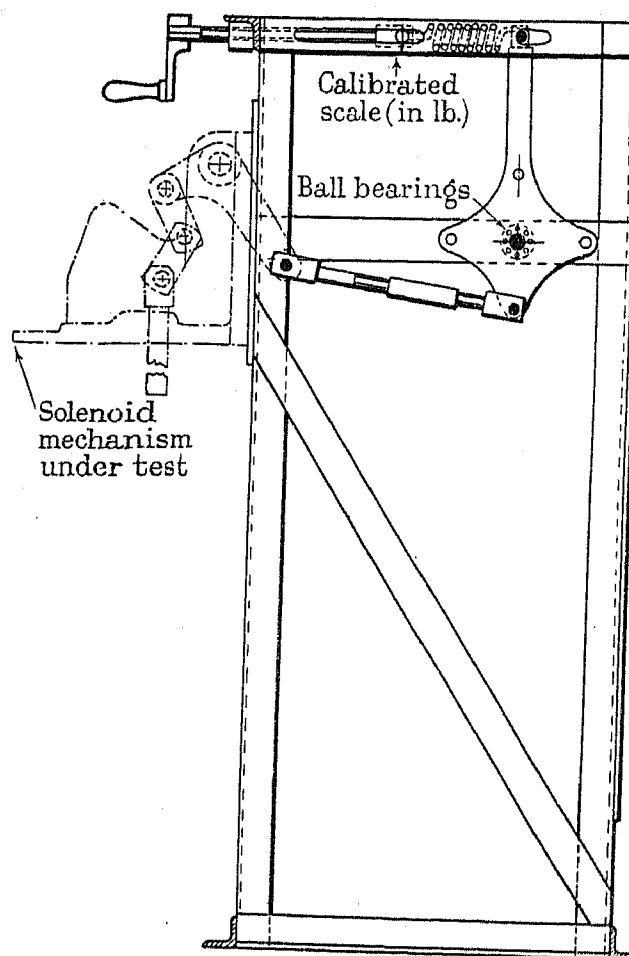


Fig. 12.—Universal form of fixture for testing solenoid and other power-operated mechanisms.

suitable for a "pull" mechanism and the other side for a "push" mechanism. The bell-crank (which is again mounted on ball-bearings) is also provided with arms to suit upward and downward applications.

The break-up force can be set to any desired figure by an adjustable spring, the exact load being indicated on a calibrated scale.

(9) CONCLUSION

In this paper an attempt has been made to give a brief survey of the mechanical limitations of oil circuit-breakers and of the care that is necessary in design and testing to reduce the adverse factors to a minimum.

(10) ACKNOWLEDGMENT

The author tenders his thanks to The British Thomson-Houston Company, Ltd., for the illustrations used in this paper, and for the interest taken in its preparation.

[The discussion on this paper will be found on page 673.]

DISCUSSION BEFORE THE TRANSMISSION SECTION, 8TH MAY, 1940

Mr. M. I. Barstow: The author's statement that no known test can take the place of the passage of time is well borne out in practice, and I feel that the user can often supply information which is of service to the designer in regard to future designs.

When the grid first started operating, the C.E.B. drew up a programme of work to be carried out every year on their plant, including switchgear. The work in connection with switch mechanisms includes monthly tripping tests, quarterly inspections and annual overhauls. Circuit-breakers are overhauled as soon as possible after faults have occurred, and the evidence often is that these overhauls prevent ultimate breakdown of the circuit-breaker. The routine tripping tests of the circuit-breaker mechanisms have also been of value.

I should like to mention one or two examples of the type of trouble that we have experienced in the S.E. England Area of the Board. The first case occurred on some new 6.6-kV switchgear in a power station with an unusually high rupturing capacity for that voltage. A circuit-breaker was taken out of service for routine tripping tests and was afterwards put back into service. A week afterwards a fault developed on the feeder, and the circuit-breaker failed to open. On carrying out tests we found that after being closed for $1\frac{1}{2}$ days the circuit-breaker would open, but after being closed for 3 days it would not open. The trouble was due to excessive friction set up by distortion of links and pins. The only remedy in this case was the strengthening of the mechanism. In another case where a switch failed to open the cause was excessive friction set up between a bakelized-paper lifting rod and a metal bush at the mouth of a housing on the circuit-breaker top plate; the clearance was so fine in this case that chafing resulted, and after a number of operations extending over 3-4 years complete seizure occurred. In several other instances of the same sort we have avoided that trouble by carrying out routine tests.

We have also had trouble on the types of operating mechanisms where ropes are employed, the trouble being due to rope stretch. On such mechanisms some means of ready and accurate checking should be provided. If the trouble is allowed to continue, it is possible for the main contacts to open and the circuit to be maintained on arcing contacts only. The following is a rather startling example of what can happen through a minor defect. A new feeder was about to be commissioned, and its associated circuit-breaker first underwent commissioning tests. When these had been concluded the circuit was switched in, and it was found that at the remote end only two of the three phases were energized. Apparently an insulator had fractured, causing a moving-contact cross-bar to fall to the bottom of the tank, presumably because the shock of the end of the opening stroke was not absorbed by an oil buffer.

Another serious type of circuit-breaker fault is often described as "opening for no apparent reason." This type of fault is generally due to instability in the tripping mechanism; manufacturers are sometimes inclined to send circuit-breakers out of their works with the tripping mechanism adjusted much too lightly. This can be a

most annoying type of fault to a supply engineer, particularly when large and important supplies are relying on one switch remaining in the closed position. Possibly the reason for the light setting is to comply with the condition that tripping devices should operate satisfactorily at 50 % of the operating voltage; but I have found cases where tripping devices will operate at less than 30 % of the operating voltage, and after a short period of service the point of instability is reached. In these days when circuit-breakers are often operated from points which may be some miles away, although it is of great importance that the condition of tripping at 50 % of the operating voltage should be complied with, there should be no attempt to reach a lower value, particularly as on important switchboards the tripping is always carried out by means of a battery.

Mr. C. J. O. Garrard: All manufacturers have to make sure that their output attains a certain standard of quality. The means to this end vary with the product under consideration, the cost of each unit and the number that are produced. If the units are few and expensive, one can afford to make service tests on every unit; if they are cheap and numerous, like electric lamps, one adopts a statistical test. A number of samples from each batch is tested to destruction. If the conditions of manufacture are controlled sufficiently closely, one can then calculate mathematically the proportion of the whole that attains a given level of quality.

Circuit-breakers are in an intermediate position. The numbers are too small for statistical testing, and the cost of short-circuit tests on each unit would be prohibitive. As far as short-circuit tests are concerned, it is therefore necessary to rely on type tests, i.e. to test one specimen of a certain type of gear and assume that it is representative of the whole batch.

The assumption underlying the type test is that chance variations in the manufacturing process do not to any important degree influence the operation of the gear. The dimensions of the parts and the quality of the material have to be the same throughout, and the same amount of care has to be exercised in building each unit.

Acceptance of a type-test certificate for a circuit-breaker implies confidence that the manufacturer, having tested one unit, will take care that all the other units are identical with the tested one. It is here that routine tests such as those described by the author become essential. The Association of Short-Circuit Testing Authorities provides still another assurance. It supplements the Standard Specifications by detailed regulations as to the manner in which tests are to be carried out, and keeps a register of all circuit-breakers tested by its members.

One sometimes forgets that long before the advent of switchgear testing stations there were many excellent switchgear installations. The engineers who were responsible for them relied above all on their engineering judgment and common sense; they compared new breakers with those of which they had had experience; they applied certain empirical rules as to oil quantities, clearances and so on; finally, but not least, they took account of the reputation of the maker. Nowadays

there is an unfortunate tendency for some purchasers to set aside their individual judgment and rely entirely upon the production by the manufacturer of a type-test certificate, which may be given after an isolated series of tests. My experience of short-circuit testing leads me to place limited reliance upon the results obtained from isolated tests; one must have repeated tests, and supplement them with considerations such as I have mentioned. Nothing can replace constant access to a testing station by designers and draughtsmen. A man who is constantly dealing with the problems that arise in testing from day to day has a great advantage over one who only has rare opportunities of witnessing tests.

I come now to one or two points arising directly from the paper. I agree with Mr. Barstow that very light trips are not desirable: they are liable to operate when subjected to vibration, or they may lead to failure to trip in the event of dirt or rust getting into the mechanism. A useful test for trip gear is to pack the breaker contacts so that they just do not touch and then to apply the maximum voltage to the closing mechanism and the minimum voltage to the trip coil. This test simulates the conditions which occur when the breaker is closed on a short-circuit and ensures that the tripping mechanism will work before the contacts are fully home, with the maximum load on the mechanism.

I agree with the author that making trips are very desirable. The advantages of a trip mechanism which, if the breaker is closed upon a short-circuit, opens it without any delay, are obvious with any breaker, and particularly so in the case of hand-closed breakers.

There are two varieties of these making trips, mechanical and electrical. Most of the mechanical devices work on the inertia principle. During the first part of the stroke some portion of the operating mechanism moves with the operating handle; if the operating handle stops owing to the breaker closing on a short-circuit, this portion of the mechanism moves on and trips the breaker. Such devices can only exert a comparatively small force, so that there is a danger that they will be rather delicate in operation and need a light trip. I prefer an electrical device which may consist of an ordinary instantaneous trip coil energized by current transformers and arranged to be cut out of circuit when the breaker is completely closed, so that it operates only during the time when the arcing contacts are closed but before the main contacts close. I find from comparative tests that the speed of operation with the electrical making trip is at least equal to, and sometimes better than, that obtained with mechanical devices. If, as is very often the case, the breaker has time-limit-fuse-shunted trip coils, these work perfectly as a making trip, because on a heavy short-circuit the fuses blow in about half of one half-cycle, and the breaker trips quite as soon as one having a special mechanical trip. Series overload trips behave similarly.

The author suggests a scheme of design which is based on static contact characteristics; these characteristics are, however, profoundly modified when the contacts are carrying heavy short-circuit currents. It would seem, therefore, that the scheme must be used with considerable caution, and that designs based on it may have to be modified when short-circuit tests are made.

The same criticism applies to the closing-force characteristics given in the paper.

This question of the design of the operating mechanism, although difficult enough, is perhaps more straightforward than most other problems of circuit-breaker design, as it is purely mechanical. In contrast, when designing parts made of insulating material one always has to compromise between mechanical and electrical requirements; in general, that can only be done as the result of experience and continued testing.

To assist our circuit-breaker designers we have drawn up a kind of catechism, including all the points (some of them only of detail) which we have learned require attention by the drawing office if later trouble is to be avoided. This is brought up to date from time to time, and has been very useful in helping to ensure that difficulties once met and overcome do not recur.

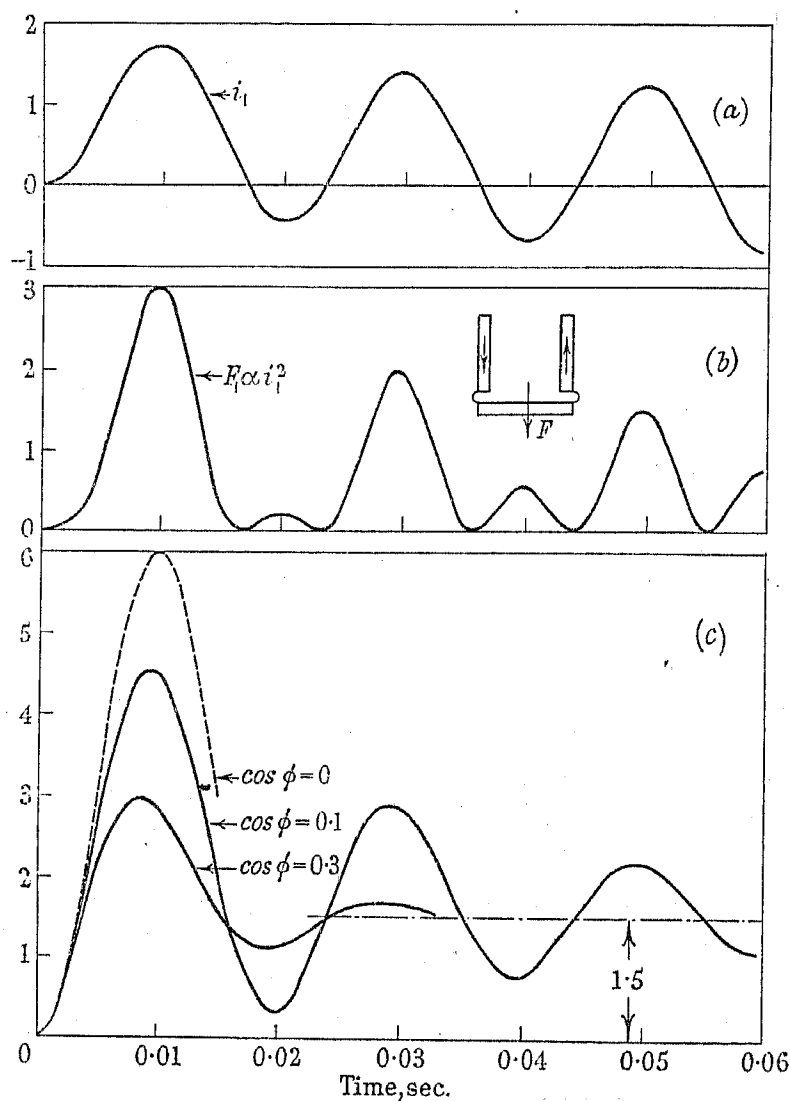


Fig. A

- (a) Single-phase asymmetrical current. $\cos \phi = 0.1$.
 (b) Outward force on a conductor loop due to single-phase asymmetrical current. $\cos \phi = 0.1$.
 (c) Sum of forces due to 3-phase currents in three conductor loops. $F_1 + F_2 + F_3 \propto i_1^2 + i_2^2 + i_3^2$.

Mr. S. Farrer: Brief mention is made in Section (4) (d) of the forces due to the electromagnetic effect of the short-circuit current. This tends to increase the stresses in the mechanism parts during short-circuit conditions, particularly on closing, and it is of interest to note the form of these forces during the initial stages of a short-circuit. These are indicated for single-phase and for 3-phase currents in Fig. A.

The provision of adequate closing power to overcome these forces brings a problem in energy absorption at the end of the closing stroke for normal switching operations and at the end of the opening stroke, due to the increased speed on the moving parts, after the breaking of heavy short-circuit currents. I should like to support the author's suggestion that mechanical inertia trips or equivalent electrical devices operative during the closing stroke may usefully be employed on circuit-breakers whose short-circuit ratings render them liable to attempts at closure against high values of short-circuit current; this applies more particularly where the extra electromagnetic forces form a big proportion of the total required closing forces.

One electrical method which has several advantages may conveniently be used with solenoid-operated circuit-breakers. It requires the inclusion in the d.c. supply circuit of a small high-speed normally-closed contactor-type switch. If fault current flows owing to the circuit-breaker being closed on to a fault, the switch is unlatched by a current-transformer-operated trip coil and the solenoid current is cut off so as to allow

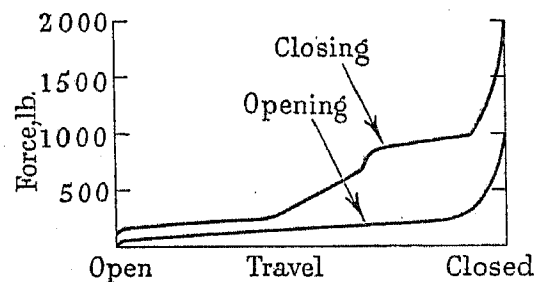


Fig. B

the main circuit-breaker to reopen immediately. This electrical device thus assists in the mechanical problem and, like the inertia trip device (this is a point not mentioned in the paper), limits the duration of the fault current on closing to a few hundredths of a second. The electrical device has added advantages of ready fault indication as well as of prevention of attempts at reclosure.

I should like to describe an alternative method of testing the mechanical forces on different parts of a circuit-breaker mechanism during closing and opening. It includes what is really a hydraulic jack which may be bolted on to the circuit-breaker closing mechanism and is charged by hand-driven or motor-driven pump. The force may be read on a static pressure gauge connected with the oil in the cylinder at any point in the circuit-breaker stroke. It may also be recorded by a scribe, deflected by pressure, over a drum having axial movement corresponding to the breaker travel. The deflection is thus proportional to the force acting at any point in the travel, and the record obtained is similar to an engine indicator-diagram, as shown in the typical record given in Fig. B. When the pump is motor-driven the breaker may be closed at any desired speed and the corresponding forces recorded. The opening speed is controlled by a release valve. The advantage of this testing device is the facility it provides for taking the force measurements and records during breaker movement under the frictional effect of sliding parts and at different speeds,

in addition to its capabilities for measurements which include static friction.

The paper has revealed some of the complex mechanical problems involved in circuit-breaker design, and it is hoped that it may serve as a plea to certain users of circuit-breakers to avoid leaving them in the closed position for long periods of time. The uncertain components of the frictional effects in the mechanism, i.e. the components due to standing under stress, will be lessened and the reliability increased if the circuit-breakers are tripped and reclosed occasionally.

Mr. W. A. McNeill: The factors of assurance mentioned by the author, which must be possessed by circuit-breakers to ensure that they will open and close

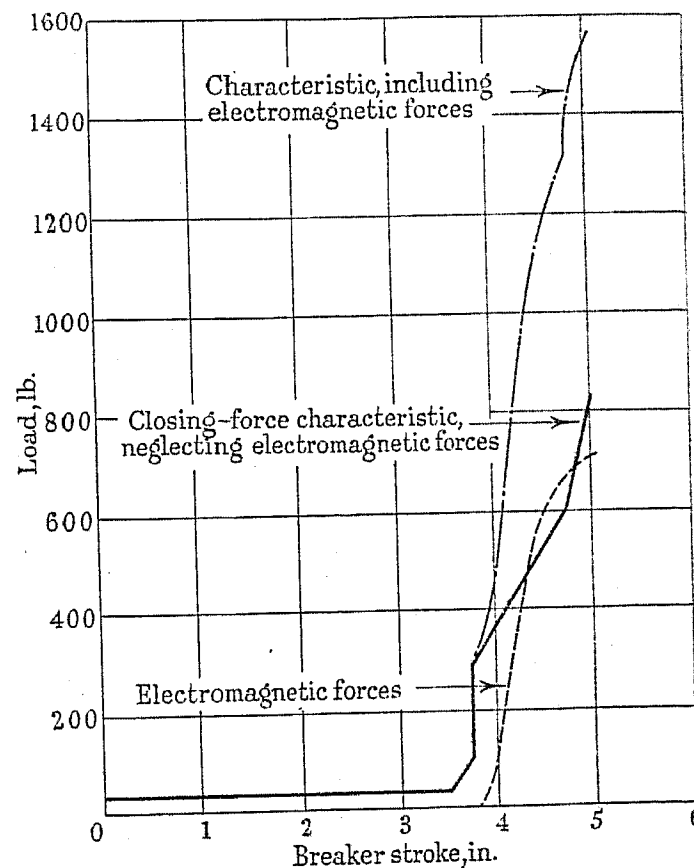


Fig. C.—Typical forces on circuit-breaker cross-bar.

satisfactorily under all circumstances, perform a useful service in that they ensure that any deviations which occur in manufacture are readily brought to the notice of the makers.

With reference to the effect of short-circuit forces on the design of mechanisms, it is generally agreed that owing to the transient nature of these forces and the infrequency of their occurrence in service, high stressing of the parts may be allowed. In certain types of breakers, however, the resulting stresses can be very high. Fig. C illustrates a case where the maximum load is practically doubled. The mechanism must be capable of closing against this additional load, and, even where inertia trips are fitted, I cannot agree with the author that these forces can be ignored. In the event of a through fault current where the breaker is latched-in and the maximum peak short-circuit forces occur, the electromagnetic forces will be transmitted to the various links of the mechanism, and must be allowed for in the design.

Two further effects of short-circuit forces may be

mentioned, which in some cases may be of a higher order than the no-load frictional effects referred to in the paper. First, a considerable increase in contact grip occurs in certain types of contacts when a short-circuit current is flowing. Secondly, depending on the value of the short-circuit current, considerable burning of the arcing contacts takes place. Those two effects greatly increase the frictional resistance that has to be overcome by the expelling force of the breaker.

Mr. F. H. Sharpe: I think the title of the paper is not quite appropriate. I would prefer: "Integrity in the design of the mechanism of electrical circuit-breakers."

The stringent testing conditions of the latest British Standard Specification for Switchgear have brought home to all the difficulties in the mechanical design of breakers. In trying to improve the efficiency of the old breakers we have on our systems, one of the problems we have to face is how much money we can afford to spend in putting in new mechanisms, which nearly always seem to be required. Any possible simplification of circuit-breaker design and mechanisms is therefore most important.

I endorse the suggestion as to the value of keeping a record of the performance of every breaker, in the works and on site tests, preferably in tabular or diagram form.

On page 670 it is stated that "a reverse force is required from the breaker to cause the levers, toggles and catch to move when the latch or prop is released by the trip circuit." Some recent experience has shown that that is very true. We had a number of breakers to which modifications were being carried out, and after certain initial troubles we got what we thought was a satisfactory adjustment. Then we found that one of the breakers would not always trip, and we ultimately found that the very simple addition of a spring made it completely reliable. This points to the need for more latitude in adjustment, because the spring was not necessary in factory proving tests. I emphasize this request for more latitude in adjustment, and I make a plea for ample and easy facilities for greasing and oiling, all the more necessary when, with the best will in the world, it is difficult to have feeders out of commission for routine testing. Automobile experience shows that grease and oil harden in bearings, allowing ingress of moisture which must be forced out periodically by fresh grease.

Mr. M. C. Hunter (in reply): I note with very great pleasure Mr. Barstow's remarks on the operation and maintenance of the switchgear on the C.E.B. system over a number of years. First-hand information from the user is of inestimable value to the designers, and the example of a breaker found to open successfully after being closed for $1\frac{1}{2}$ days, but not after 3 days, is of particular interest and shows the importance of a factory test which will indicate that there is a definite margin in favour of the breaker opening and not just a proof that it will open repeatedly on an endurance test.

Oil circuit-breakers correctly designed and backed up by a complete system of maintenance such as is employed by Mr. Barstow, should provide almost infallible service.

The fault described by Mr. Barstow as "opening for no apparent reason" can no doubt result in very serious consequences should it occur, but this fault is in my

experience almost non-existent in the case of tripping devices of the form with which I am most familiar. The successful tripping mechanism to which I refer is one without any adjustment, the stability being obtained by the inherent design of the parts. The essence of this design is that the final member to be released by the trip coil should be of truly generated radial form, acting as a prop against the last loaded member of the mechanism. A prop of this description has no bias to move in either direction under light or heavy loads or under any conditions of vibration. A small spring or a gravity bias is required to ensure resetting, but this only adds to the stability. Experience shows that this form of prop can be used on the heaviest of mechanisms and also on the smallest of hand closing mechanisms, down to direct tripping values of 3 VA.

In reply to Mr. Garrard, I would state that short-circuit testing, although admittedly the most important of all the tests to which a breaker is subjected, does not prove that a breaker will not stay closed when tripped after a period of rest. I am indebted to Mr. Garrard for his description of a simple test to simulate certain conditions which occur when a breaker is closed on to a short-circuit. In reference to his remarks to the effect that the stresses may be profoundly modified when the contacts are carrying heavy short-circuit currents, this point is touched upon in Section 4(a) of the paper. As regards the frictional forces, I prefer to base these on static considerations, as the friction is considerably greater when the parts are at rest or moving very slowly than when they are in rapid motion.

I should like to thank Mr. Farrer and Mr. McNeill for their contributions to the discussion on pre-tripping and on the transient effects of short-circuit forces. The method of testing the mechanical forces on closing and opening of the circuit-breaker by a hydraulic device, as put forward by Mr. Farrer, is particularly intriguing.

My observations on short-circuit forces in Section 4(d) were never intended to convey that such forces could be ignored, but rather that means were to be employed to reduce the result to a level where the stress could be dealt with and adequately catered for in the design. Under conditions of short-circuit a much higher working stress for the material is permissible than could be allowed for non-transient forces.

Mr. Sharpe considers that the title of my paper is not quite appropriate. If we substitute the dictionary alternative for the word "integrity" we get "mechanical soundness in the design of electrical circuit-breakers," which does not appear to be very far from the subject matter covered. Any reference to tanks and top plates which might have been included in the paper was intentionally left out, as the design of these containers may be carried out on the basis of conventional factors of safety, once the maximum internal pressure has been assessed.

I am pleased to learn of Mr. Sharpe's experiences in connection with a breaker which would not always trip out. The facts of the case further endorse my views as to the need of (a) "factors of assurance" in the design, and (b) routine factory tests to prove that adequate margins are available. Had this breaker been designed and tested as specified in the paper, the need for the

simple addition of an extra spring would have been disclosed before the breaker had left the manufacturer. Whilst agreeing with Mr. Sharpe's plea for ample and easy facilities for greasing and oiling, I believe that the number of points for adjustment should be reduced to a

minimum. Too many adjustments are a curse—especially if these have to be carried out in series and (as in many cases) are merely an excuse for the designer to modify, after assembly, margins which might well have been decided in the drawing office.

DISCUSSION ON “HIGH-VOLTAGE DISTRIBUTION IN RURAL AREAS”*

Mr. P. W. Blakeley (New Zealand) (*communicated*): The author has taken considerable pains to point out the superiority of copper conductors over steel, but he completely ignores the other competitor in the field, the composite steel-aluminium conductor. Has he made any investigations to ascertain whether lines using such conductors would not possibly be a useful compromise between low-stress short-span copper lines and high-stress long-span steel lines?

New Zealand can claim to be well to the fore in supplying its isolated inhabitants with electricity, and the general practice here is to use copper conductors for h.v. rural lines. No. 10 or No. 8 S.W.G. conductor was formerly used for such lines, but the 1935 Supply Regulations required the use of stranded wire, and either 7/16 or 7/14 conductor is used now for rural lines. No. 8 S.W.G. galvanized iron or steel conductors have been used with success for supplying small groups of consumers with a combined load of 20 or 30 kW where the distances are not too great, and the use of such conductors is permitted by the 1935 Regulations. Fig. 19 in the paper shows that for loads of this magnitude the use of copper conductors would not be justified by the resultant saving in the annual cost of line losses.

I gather that in the type of transformer-pole arrangement described in Section (11) the transformers are not individually fused on the h.v. side. How many transformers are thus grouped under the one protective arrangement? Does it not mean that an unduly large number of consumers will be affected by a breakdown in one transformer? Fig. 29E shows an apparently unprotected transformer at the end of a h.v. line, a position where it would be particularly susceptible to damage from lightning. Has any trouble been experienced from this cause?

Mr. W. F. Davidson (U.S.A.) (*communicated*): To an American this paper and the discussion serve to emphasize the similarities and the differences in the problems facing electrical engineers in England and America. I wish to comment only on two points of difference which are of special interest to me because of my position as chairman of the power system representatives on the Joint Plant Co-ordination Committee—Edison Electric Institute and Bell Telephone System.

First, it comes almost as a shock to note the obstacles that had to be overcome before even a limited degree of

common pole use by power and communication circuits was attained. In the United States “joint use” is a procedure that has been recognized and practised for many years as an essential to the solution of the broad problems of providing communication and power to a community. As was to be expected, there have been some technical and operating difficulties, but for the most part they have been minor. Numerous published reports attest to their analysis and solution. Among these are the Engineering Reports (particularly Nos. 6 and 13); Provisional Report 19, “Joint Use of Poles—Telephone Circuits and 6·6- and 13·2-kV Power Circuits—Safety Features”; and “Specifications for the Construction and Maintenance of Jointly Used Wood Pole Lines carrying Supply and Communication Circuits”—all issued by the Joint Committee. The economic aspects require specific analysis in each case, but the methods to be followed are obvious.

Second is the reference to earthing practice and particularly Mr. Frost's apprehension, as expressed in the discussion, that multiple earth connections will increase seriously the problems of telephone interference. The trend in America is very definitely towards the use of multiple earthing, and also common earth connections for high-voltage, low-voltage and communication systems. Engineering Report No. 40 “Inductive Co-ordination on Rural Power and Telephone Systems” summarizes the work on interference up to January, 1938. Further studies are in progress. Earthing is discussed at some length in “Principles and Practices in Grounding”—a Committee Report of the Edison Electric Institute issued in 1936.

Mr. K. L. May (*in reply*): Mr. Blakeley rightly claims that to-day New Zealand is well to the fore in supplying isolated premises with electricity, and it is interesting to learn that the general practice is to employ light copper conductors for rural lines.

I do not favour S.C.A. conductor as a compromise between steel and copper for rural lines, and I would add that if a compromise is necessary for any particular scheme, then cadmium copper, steel-cored copper, copper-cored steel, etc., should be considered in addition to S.C.A. All of these alternative types of conductor offer longer-span construction than copper conductors, but if they are erected to the conditions outlined in the Commissioners' circular letter M.2854 it is possible to obtain line tensions which may be dangerously high and thereby introduce vibration troubles with consequent

* Paper by Mr. K. L. May (see page 33).

fracture; this applies particularly in the case of S.C.A. Points made in the paper and in my reply to Mr. Purse regarding long-span lines of light construction, apply also to S.C.A. conductors.

I note with interest that No. 8 S.W.G. galvanized-iron or steel conductors have been used for supplying isolated small groups; during the past 7 or 8 years similar conductors have been used in England for short spur lines supplying isolated farms and houses. From a first-cost point of view, the practice appears sound, but in some cases it has been found that severe corrosion takes place at the point where the conductor is bound to the insulator, I am therefore uneasy regarding the stability of this type of line after 10 to 15 years, or in some cases even earlier, when rewiring may be necessary.

Mr. Blakeley is correct in assuming that h.v./l.v. transformers on combined construction schemes are not individually fused on the h.v. side, protection being carried out at the h.v./h.v. transformers. This practice has been followed because experience with fuse-protected small transformers on 11-kV networks proved that the fuses operated due to lightning, thereby isolating a group of consumers, whereas other transformers, not fused, were unharmed. Examination also proved that a greater number of consumer-hour "outages" took place through fuses protecting individual small transformers failing unnecessarily than is the case when an unprotected transformer fails and thereby isolates a greater number of consumers through operation of a circuit-breaker at

the source. In other words, the number of consumer-hours lost by the operation of fuses on each small transformer is greater over a period than is the case on the rare occasions when a larger number of consumers is affected owing to the operation of a circuit breaker at the source. Credit must be given to the very high standard of reliability of present-day transformers, which is chiefly responsible for the success of this practice. Twelve h.v./l.v. transformers constitute the greatest number which have been installed to date on any individual combined h.v./l.v. scheme.

It is common practice to erect transformers at the end of spur lines without special protection against damage from lightning, and although isolated cases have occurred where a transformer has been damaged these are so very few that standardized protection could not be justified for the many hundreds of transformers erected in similar positions.

I am very grateful to Mr. Davidson for his comments and also for calling attention to the Reports of the Edison Electric Institute, which contain valuable data and recommendations concerning the operation of telephone and power circuits on the same pole.

It is interesting to have confirmation that although some technical and operating difficulties arose in connection with the joint use of poles they were generally of a minor character; also that the policy of "joint use" has been recognized and practised in the United States for many years.

DISCUSSION ON

"OPERATING EXPERIENCE WITH HIGH-VOLTAGE ALTERNATORS"*

FURTHER WRITTEN CONTRIBUTION TO THE GENERAL DISCUSSION†

Mr. A. E. F. Spence (South Africa) (*communicated*): Consideration of the points dealt with in the paper seems to indicate that the h.v. neutral point of the voltage transformer should be insulated from earth. Can the author say why this was done in the first Brimsdown machine, and not in the second one? Mention is made of the cost of a high-voltage bushing on the transformer chambers of switchgear of the phase-isolated type. This seems to be a defect of this type of gear. I should be glad if the author could give any comparison of the cost of such bushings and that of apparatus for suppressing neutral inversion.

I do not follow the author's explanation of the failure of machines No. (4) and No. (6) at Salt River. This might well apply to periods when the machine was running up or down disconnected from the system, and under full or partial excitation. The failures occurred after some hours on load, particularly that of No. (4) machine, which had been running all day at nearly full load.

Finally, does the author think any improvement would accrue from running 33-kV alternators in hydrogen?

[The author's reply to this discussion will be found on page 684.]

NORTH MIDLAND CENTRE, AT LEEDS, 17TH FEBRUARY, 1940

Mr. F. Gurney: To go back 11 years in the history of 33-kV generation is to go back to the pioneering days. The justification for this pioneering is evident from the Table, giving a list of high-voltage alternators that have been built. This list indicates that there is a demand for 33-kV generation. Many city undertakings are already solving their problems of switchgear limitations and cable congestion by adopting 33-kV distribution.

The author analyses under three headings the troubles encountered: (1) conductor insulation, (2) joint insulation, (3) over-voltage caused by neutral inversion.

I agree that there should be no trouble whatever with conductor insulation. Only one accident of this sort is recorded, and plenty of evidence is given to suggest that the care now taken should prevent future troubles. But the whole conception of the concentric-conductor design is based, apparently, on the fear of conductor trouble. The concentric conductor is merely a voltage-grading device. Equally effective voltage-grading can be achieved with the condenser-bushing type of conductor, which does not lead to any troubles such as are described under the heading "Joint Insulation." We can draw a parallel with the old-type concentric cable, which, although having excellent qualities, cannot be used up to high voltages on account of trouble at the joints.

I disagree with the author's remark (page 350) "The advantage of thoroughly impregnating completed windings with insulating varnish in order to eliminate air spaces is recognized widely, and the only reasons for not applying this treatment to large machines are the high cost of, and large amount of space occupied by, the necessary equipment." Impregnation under vacuum should be done during the process of making the individual windings, when it is possible to get the varnish to the points where it is needed.

I notice on page 351 the remark "After the cycle has

been completed, dry heated air is circulated through the tank in order to oxidize the varnish." I presume oxidation of the varnish is the process of hardening it. Emphasis is laid on getting the varnish into every nook and corner; but how then does the oxygen get there also for hardening purposes?

On page 345 it is stated "The bar was replaced in a few days, and this experience served to demonstrate the rapidity with which a bar can be replaced in the concentric type of winding." Was it not necessary for the machine to go through the impregnating plant?

Mr. W. T. J. Atkins: The author has been unfortunate in that some of the machines he has designed have been subjected to excessive voltage-stresses due to conditions of operation which he had no reason to foresee. The circumstances emphasize the importance of considering methods of earthing in relation to systems or assemblages of plant as a whole, rather than in relation to individual items of equipment.

The paper refers generally to the phenomena classed as neutral inversion, and points out that they are usually encountered in connection with instrument transformers associated with phase-isolated switchgear. I had personal experience of such a phenomenon a few years ago, when an oscillograph showed the presence of parasitic voltages having a frequency slightly differing from half the system frequency. The effect was one of the types described in the author's Bibliography, and according to the published information it should have been possible to prevent it by connecting damping resistors across the voltage-transformer secondary terminals, but attempts to do this proved unsuccessful. Fortunately, the abnormal voltages produced were not in this instance of a dangerous character, so that the occasional production of neutral inversion, although inconvenient, was harmless.

Prof. E. L. E. Wheatcroft: It is a well-known fact in laboratory practice that every item of equipment, and

* Paper by Mr. W. D. HORSLEY (see 86, p. 345).

† See 86, p. 354.

particularly equipment liable to high voltage, should have its potential fixed with respect to earth; and there is no doubt that this principle still holds when the plant is removed from the laboratory to a power system. In the past, power engineers have often been in the habit of regarding the neutral-earthing equipment as being designed merely with the object of relay operation, whereas there is little doubt that its primary purpose ought to be the fixing of system potentials. Looked at from this point of view, the fear of multiple earthing which has been engendered in power-station engineers by earlier Post Office requirements may easily have unfortunate results. My point is that it is far better from the point of view of fixing potentials to have too many earthed points rather than too few. In particular, it should be realized that a generator which is being run up and is about to be synchronized is a separate system, as also is a generator which is being disconnected. It is therefore essential that the potentials of these generators should be fixed by a neutral-earthing device, and that there should be temporarily (for perhaps only a matter of seconds) a multiple earth on the system just when these generators are being connected.

It is clearly much easier to apply the principle to a generator which is being connected than to one which

is being automatically disconnected on fault, and it is probably just on the latter occasion that the system is most liable to abnormal voltages. Nevertheless, it is, as Mr. Atkins said, most desirable that the neutral-earthing arrangements should be worked out as a complete system, and this should include if necessary automatic arrangements which ensure that a generator when being disconnected is not left isolated from earth. Otherwise voltages are determined by strange things, such as capacitance, of which the designer has no knowledge and over which the operating engineer has no control.

Mr. R. Wall: Electrical engineers have for some time been looking forward to 66-kV generation, and I think the author is helping to make it an accomplished fact.

Mr. Gurney mentioned that 33-kV distribution is popular; but 66 kV would be a more convenient voltage to use for supplying the C.E.B., which takes the bulk of the load from the big power stations. So far as transformer efficiency is concerned, the difference is small between 11-kV to 66-kV and 33-kV to 66-kV transformation. I feel that whilst we are doing a tremendous amount of development with 33-kV generation, we should regard this only as pioneer work for 66-kV generation.

[The author's reply to this discussion will be found on page 684.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 19TH MARCH, 1940

Mr. J. A. Kuyser: I think we must concede that in general the concentric-conductor alternator has proved successful, but I believe there are other and better ways of dealing with the problem of 33-kV generation.

for 0.8 p.f. it must have been operating at 80 % of its rated current, and therefore at two-thirds of its normal temperature-rise on the end connections. This has been perhaps very fortunate in that it may have prevented

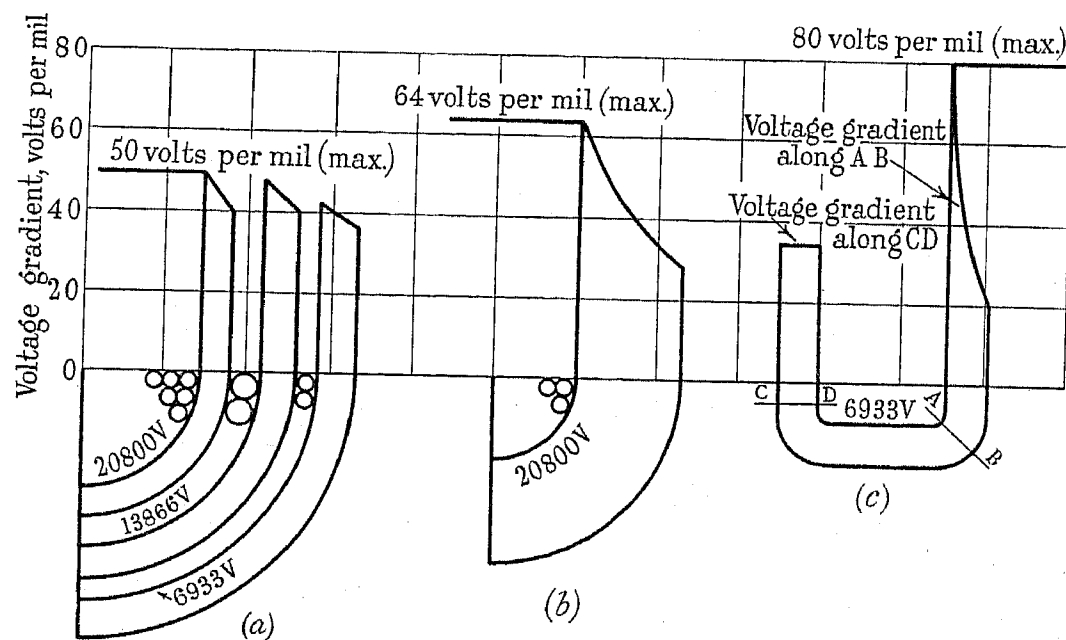


Fig. C.—Curves showing voltage gradient through insulation on various types of conductors. (Increase in gradient due to strands of cable = 23 %.)
 (a) Concentric conductor for 36 000-volt alternator. (b) Single-core conductor for 36 000-volt alternator. (c) Rectangular slot for low-voltage (11 000 volts) alternator design.

I notice that a large percentage of the troubles mentioned in the paper have occurred at the joints. In particular, the failure at Swansea was due to a combination of overheating at the joints and defective insulation. Regarding the first Brimsdown alternator, which has been in operation for 11 years, the power factor of the load at Brimsdown is unity, and since the generator was designed

trouble similar to that at Swansea, which might have prejudiced operating engineers from the start against 33-kV generation.

Regarding the joint construction shown in Fig. 3, I quite agree that the insulating bushes are a very important feature of these joints. Their function is somewhat similar to that of the stress cones used in cable

boxes. There is a bush between the bull and the inner conductor, and one between the inner and the outer, but there is no bush between the outer and the core. This is a bad feature, because the creepage distance between the core and the outer is relied upon as being an equivalent to a bush, and this distance is too short for the purpose. The potential of the outers is normally only 11 kV, but the potential due to feeder faults and surges is considerably greater.

There is considerable danger of failure due to surges, particularly if the generator is operating on an overhead line, even if there is a short length of cable connected between the overhead line and the generator. In the case of a feeder fault, the inner section reaches a voltage of 24 kV to earth, but there is a likelihood of a surge emanating from the fault, particularly if the star point is insulated. We have made an investigation with the new type of recurrent-wave cathode-ray oscillograph, and we have found that the wave travels through the winding and is reflected at the insulated star-point, and at the moment of reflection the voltage is almost twice the voltage of the incoming wave.

If an earthing resistor is used, the reflection can be eliminated, and it is advisable to have a resistor between the star point and earth on every generator which is connected to the busbars (multiple earthing). The resistor should have a value rather less than the surge impedance of the winding, which is of the order of 500 ohms. A resistor of about 200–300 ohms is generally used.

The claim is made for the concentric-conductor alternator that it is immune from surges due to the high capacitance between sections. The published curves (86, p. 366) show that the potential difference between winding sections is approximately one-third of the voltage of the incoming wave when the star point is earthed. It would be interesting to see curves taken with the star point insulated, which will show higher internal voltages. The maximum voltage between turns of the single-conductor winding is approximately one-third that of the incoming wave if the star point is insulated; and the two types of winding are therefore similar in their behaviour as regards surge distribution. The single-conductor winding has the advantage of full insulation on each conductor, and double full insulation between turns.

Fig. C gives the manufacturer's curves showing the distribution of voltage gradient through the insulation on various types of slot conductors. The maximum gradient on the bull conductor is given as 50 volts per mil. On the 11-kV rectangular conductor, at (c), the stress at the four corners is given as 80 volts per mil, this high value being due to the stress concentration at the corner. The stranded cable shown at (a) has a small radius to every strand, however, and there is a stress concentration of 23 % at every one of these strands. A similar stress exists on an overhead transmission line, the corona limit of a stranded cable being lower than that of a smooth conductor. If we allow for the concentration due to stranding the gradient becomes 62 volts per mil.

In order to control the stress distribution in the single-conductor winding, each conductor is made in the form of a condenser bushing by means of conducting shields (Fig. D). Each grading shield has a potential which can be calculated in the same way as that in a condenser

bushing. There is an extra stress due to the fact that the bar is rectangular, and also an extra stress due to the corners. These stress concentrations can be determined by means of the method described by Cockcroft.* The average gradient between the conductor and the inner shield is about 16 % higher than the average over the whole thickness, which makes it about 52 volts per mil. The extra stress at the corners is 25 %, so that there is a maximum local stress of 65 volts per mil. The gradients

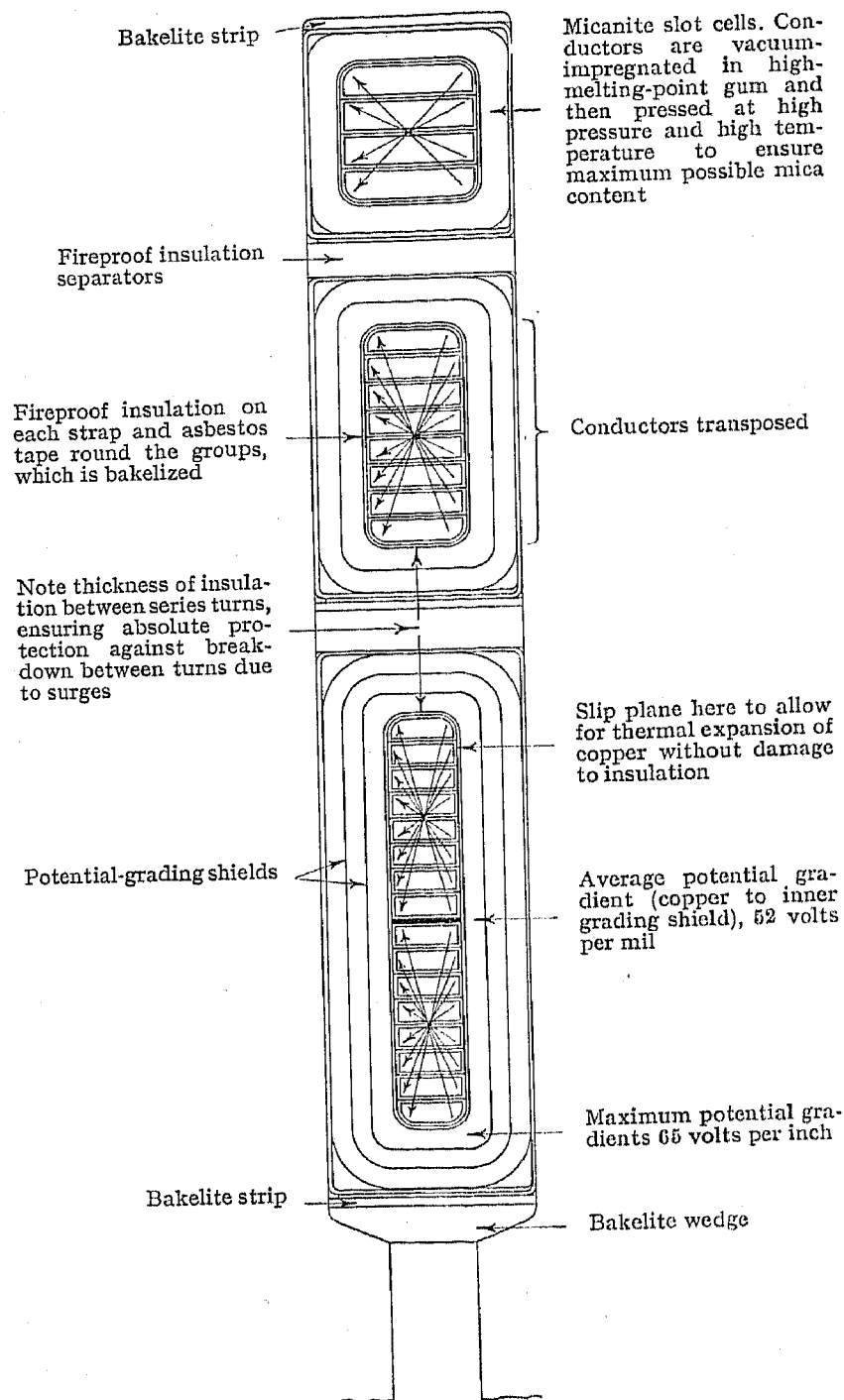


Fig. D.—Stator slot, 33 000 volts.

obtainable in the rectangular conductor with grading shields are therefore the same as those obtainable by means of a concentric conductor. The longitudinal gradient at the end of the conductor outside the core, obtained by means of the grading shields, is similar to that of a condenser bushing. The local gradient at the end of the core is divided into three smaller gradients which are roughly equal.

I take the opportunity of giving some further details of the single-conductor winding. It consists of three com-

* *Journal I.E.E.*, 1928, 66, p. 385.

pletely separated windings wound for 11, 22 and 33 kV respectively. The 11-kV winding is at the bottom of the slots, and this winding is first completely finished; the 22-kV and 33-kV windings are then placed in position.

It will be noted that the bars join the connectors in a large curve, and it is very easy for the workshop to insulate the joints perfectly. The insulating tape can be applied uniformly, almost as on a cable, and the thickness of insulation can be made adequate. As a result the joint is almost as strong as the remainder of the end-connectors. A complete conductor and a connector jointed together were immersed in salt water, and after 5 weeks a voltage test of 80 kV failed to cause a breakdown, but flashover took place between the connector and earth over a length of 4 ft.

Mr. F. A. Youngmark: Some of the failures which form the subject of the paper were caused by conditions external to the machines, such as neutral inversion or the presence of salt and moisture in the closed air circuit. Can the author state how the entrance of salt and damp air into the Salt River alternators was prevented? In practice, it is difficult to keep the alternator closed air circuit completely free from leaks, and in attempting to do so there is a risk of reducing the internal pressure on the high-pressure side of the ventilating fan down to, or even slightly below, atmospheric pressure, which of course involves a partial vacuum on the inlet side of the fan. If this condition exists there is a risk that oil vapour from the bearings may be drawn into the alternator. The usual method of preventing this is to arrange a small leakage path in connection with the external atmosphere on the inlet side of the fan, and to pass any make-up air through a filter. By this means the whole of the closed circuit is maintained at or above atmospheric pressure, assuming there is no excessive leakage on the delivery side of the fan. Was this practice adopted at Salt River, and, if so, was the filter effective in keeping the cooling air free from salt and moisture?

Other failures have been caused by weaknesses in the alternators. Two of the breakdowns on the second Brimsdown machine were due to actual punctures of the insulation tubes, but it seems clear from the paper that the cause of these failures is known and has been eliminated by better manufacturing methods, testing and inspection. The remaining breakdowns have involved the T-joints between the slot bars and the end connections. Anyone who has had the opportunity of examining one of these joints in detail cannot have failed to be impressed by the high standard of design and workmanship displayed in its manufacture, and that this type of joint can be made as reliable as any other part of the winding is proved by the fact that the first 33 000-volt concentric-conductor alternator has run for over 11 years without trouble.

The fact that one or two later machines have not been equally satisfactory can be explained by considering manufacturing conditions. The progress of the first machine of a new type through the shops is watched with anxious care by its designer and by everyone else concerned, and there is general relief when works tests and operation at site show that hopes and expectations have been realized. The process of winding a large alternator involves great care and skill on the part of the workmen. While inspection of machining processes can be both

exact and complete, it is far more difficult to carry out continuous inspection during processes such as winding and the application of insulation. The need for close inspection is perhaps greatest after the novelty of the first machine of a new type has worn off, and until labour has, by frequent repetition, been fully trained in what may at first be novel work. More thorough inspection would no doubt have led to the rejection of the defective mica bushes referred to by the author.

Now that the importance of these small points is realized, the stator end-winding joints (Fig. 3) are no longer a source of weakness. The company with which I am connected has recently carried out an extended series of breakdown tests on these joints, and in every case failure has occurred by puncture of the insulating tubes surrounding the conductors, and not between joints.

Mr. W. Kidd: Our operating experience with a 71 500-kVA 33-kV machine has been entirely satisfactory; during the past 2 years the set has been on load for 96.5 % of the time, and the load factor has been 88 %. Experience elsewhere also has demonstrated that 33-kV machines are reliable if the conditions on the system are satisfactory. Some of these conditions the machine designer does not bother about. In new stations the matter is fairly straightforward, but in old stations generating at a lower voltage more difficulties present themselves.

During consideration of a scheme for the installation of four additional machines, I was reluctantly forced to the conclusion that the necessity of flexibility of arrangements for load transfer to various feeder sections during various stages of station loading, and also for dealing with short-circuit kVA, made the selection of a lower generating voltage the better proposition.

The machine characteristic in which the station designer is much interested is its reactance. What does the author consider is the maximum percentage reactance that can safely be adopted? I have used a figure of 25 %.

The cable connections to the machines should be very carefully designed; for civil-engineering reasons I prefer that the terminals should be arranged in the orthodox manner at the end of the machine. One maker, however, arranges the terminals on the side of the machine. Does the author see any objection to this? In one case at least I suspect that the ozone noticed comes from badly designed bare-copper connections to the set. Our practice has been to bring cables to the machine and make a good insulated connection to the windings.

Neutral inversion can be avoided, and should not be a cause of trouble in the future. The neutral of our system is earthed, and at the maker's request we also earth the neutral of the incoming machine; after the set has been connected to the busbars one of the neutral circuit-breakers is opened. I should certainly prefer not to leave the system unearthed.

I believe the earlier 33-kV machines had rather a low efficiency at low loads, when compared with that of a lower-voltage set. This is not a matter of great importance, because large sets are not operated at low loads, but I should like to know whether this characteristic has been changed on the author's later sets.

He mentions that, in a number of cases, trouble has been experienced due to heating of the neutral liquid resistor. If the electrodes were steel discs I would

suggest that they were, to a large extent, the cause of the trouble, owing to skin effect causing heating of the disc. A horizontal plate is a bad heat-dissipator, and heating becomes cumulative. The fitting of copper cylinders would improve matters.

Does the author see any disadvantage in the use of 33-kV machines in stations where they would be taken out of commission every night and run on light load for half an hour every midday?

Mr. H. G. Bell: About 2 years ago it was necessary for us to carry out some tests on protective gear which involved the application of short-circuits to the 132-kV grid system. The most convenient arrangement involved feeding an isolated section of the grid from a 50-MW generator wound for 33 kV. We approached the manufacturers regarding the use of the machine for this purpose, and they raised no difficulties whatever. The tests were duly carried out, and the generator showed no signs of distress. This indicates the faith the designers themselves have in the robustness of the 33-kV winding.

Mr. J. L. Carr: With high-voltage alternators some ozone generation is to be expected; and on 33-kV machines the effect is likely to be much more pronounced than on lower-voltage machines. The machine referred to by Mr. Kidd, however, has caused no perceptible odour during its period of operation, although a pronounced smell of ozone has been noticed near similar machines in another location. The method of connection may possibly have a marked influence on this matter: in the first case, cable connections are continued to the machine terminals, whereas in the other case, bare copper connections are employed; and increased discharge from these connections is to be expected.

The neutral-earthing of high-voltage generators is apparently a matter on which a good deal of divergence of opinion exists, but presumably the conditions, so far as the machines are concerned, must be improved by maintaining the neutral earthed through a resistor. Some minor difficulty due to boiling was experienced in one case where a liquid resistor was used, although this was the only system earthing point. The current flowing was primarily a triple harmonic, with a higher harmonic superimposed. The effect was not noticed when the normal metal-grid resistor was used, and only a slight increase in temperature was observed. The difference was, of course, due to the different temperature characteristics. The author states that operating engineers consider the possibility of losing the system neutral to be a normal operating risk. That was the case even with lower-voltage systems, but with 33-kV systems the risks are considerably greater. In at least two cases in other districts, of which I have some knowledge, the loss of the 33-kV neutral during a period in which faults persisted on other connected apparatus was responsible for more extensive consequential damage. Each case should therefore be considered on its merits. In one large undertaking where the busbar system is fully sectionalized, it is now considered desirable not only to earth the neutral of the direct-generating machine, but also to maintain an earthed neutral on another section, so that in the event of one machine being disconnected the system will still be earthed. Separate resistors are to be used, and direct coupling of the neutrals avoided. So long as the

busbar sections are loosely coupled, it would appear, from preliminary observations, that the risk of excessive circulating current is not likely to be serious.

Mr. G. H. Sammons: The principal causes of trouble with concentric-conductor alternators are the dangers of neutral inversion and the difficulty of making satisfactory end-connections; the improvement of these is entirely in the hands of designers. Can the author give his reasons for stating that neutral inversion will not occur again? Can a machine be so designed that neutral inversion is impossible?

The author's method of improving end-connections appears to me to be a somewhat "patchy" treatment, and I am of the opinion that some major modifications will have to be made before a permanently satisfactory end-connection is produced.

Mr. W. D. Sutcliffe: The use of metalclad switchgear appears to have led the generator designers into a certain amount of trouble, because it caused them to use three single-phase voltage transformers connected in star across the alternator, and this is not very good practice. It would have been worth while to alter the gear so that single-phase transformers could be used.

With regard to the earthing of alternators, there is no harm in earthing the neutral point of each machine. This has been done in one station where there are two 33-kV alternators running in parallel, and so far it has not caused any trouble. The author recommends that the earthing resistor should be of such a value as to allow the full-load current to pass, but this seems to be rather a high upper limit where there are overhead lines on the system, and where the biggest trouble is earth faults. Full-load current passing through the earth fault might cause a considerable amount of damage to the overhead lines.

As regards the earthing of 33-kV systems, it is essential that the neutral earth-connection should be maintained on all parts of the system as far as is practicable. In the case which Mr. Carr mentioned, where serious damage was caused by part of the system becoming earth-free, there was no earthed neutral on the part of the system involved.

One point which the author does not mention is the question of preventing high voltages on the alternators caused by surges passing along the overhead lines, such as occur when lightning strikes the line. Is it necessary to fit spark-gaps to the machine? Several machines have been damaged from this cause.

Mr. W. N. Kilner: For comparison with the author's Table of high-voltage concentric-conductor alternators, Table A gives a list of single-conductor type high-voltage turbo-alternators built, or at present under construction, in Manchester. These machines, of a total capacity of 688 310 kVA, have stator windings of the single-conductor type in which each series turn is in a separate coil, and the insulation to earth is graded in three or four steps between the star point and terminal ends of the winding. No faults or troubles have been experienced with any of the machines in service.

The smell of ozone seems to worry a number of operating engineers, but it should not cause alarm as it has been proved that the minute discharges which produce ozone do not damage the micanite insulation of modern turbo-alternators. The 20 000-kW 11 000-volt turbo-alternators installed 25 years ago in the North

Tees power station were among the earliest machines in this country to create a noticeable smell of ozone, and they were also among the first of the machines to operate with closed air circuits. They were 40-cycle alternators, and a few years ago were re-wound for 50 c./s., but before the old windings were stripped they were pressure-tested to breakdown, which occurred at 40 000 volts. The stator conductor insulation was carefully examined for any signs of deterioration due to ozone or discharges, but although the slot liners were found to be riddled with small punctures the mica insulation immediately under

and it would be interesting to know whether they have proved to be more efficient than 11-kV machines, and if 66-kV machines are expected to be still more efficient. With reference to neutral earthing, care must be taken when installing neutral-earthing resistors to ensure that they are adequate to carry the triple-harmonic currents. Liquid earthing resistors have a negative temperature-coefficient, and unless they are of ample capacity there is a danger of the liquid boiling away. If the resistor is connected in series with a small reactor a smaller resistor can be employed than would otherwise be required. The

Table A

LIST OF HIGH-VOLTAGE TURBO-ALTERNATORS OF THE SINGLE-CONDUCTOR TYPE, IN SERVICE OR ON ORDER

Name of purchaser	No. of machines	Destination	Voltage	Speed	Rating
			kV	r.p.m.	kVA
Belfast Corporation	1	Harbour	33	3 000	37 500
Bradford Corporation	1	Valley	33	3 000	37 500
Cardiff Corporation	2	Roath	33	3 000	37 500
County Borough of Ipswich	2	Cliff Quay	33	3 000	56 250
Liverpool Corporation	2	Clarence Dock	33	1 500	66 666
London Power Co.	1	Deptford	22	1 500	58 800
Manchester Corporation	1	Barton	33	1 500	71 428
North Metropolitan Power Station Co.	1	Brimsdown " A "	33	3 000	38 800
	1	Brimsdown " A "	33	3 000	25 000
	1	Brimsdown " B "	33	3 000	43 600
	1	Brimsdown " B "	33	3 000	19 550
	1	Willesden	33	3 000	35 300
Total					688 310

the liners was undamaged. I have examined a large number of machines of various voltages up to 33 kV in various power stations, and the machine which I find gives the strongest smell of ozone is an 11 000-volt generator. It does not give any trouble, and to my knowledge no trouble associated with ozone has ever occurred on turbo-alternators. When the original paper by Sir Charles Parsons and Mr. Rosen* was read, I, among other speakers, suggested that a 33-kV alternator could not have as high an efficiency as an 11-kV machine. Since then, the author has had a number of years of operating experience with 33-kV machines, with opportunity to test their efficiency,

* *Journal I.E.E.*, 1929, 67, p. 1065.

reactor will limit the triple-harmonic current without affecting the 50-cycle fault current or the normal operation of the protective gear. Mr. S. R. Mellonie: The opening of the connection between the neutral point and earth does not necessarily cause trouble or damage. On the contrary, I know of two cases where it saved the situation on a 33-kV cable system by interrupting a busbar fault. With reference to the proportion of the total reactance which is changed from transformer reactance to alternator reactance when one puts in a 33-kV set compared with the usual arrangement of machine and transformer, does the decrease in percentage of real reactance result in a more stable machine?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. W. D. Horsley (*in reply*): In reply to Mr. Spence, the switchgear connected to the first high-voltage alternator at Brimsdown is of the open type, and this fact enabled the voltage transformers to be connected between phases as shown in Fig. 2. Two single-phase units were provided, and connected in open delta in accordance with accepted practice for metering transformers. The switchgear for the second high-voltage alternator at Brimsdown is of the phase-separated type, and five single-phase voltage transformers in separate casings with the neutral end of the winding earthed to the casing

were provided. While it would have been permissible to make a small sacrifice of the principles and advantages of phase separation by isolating the neutral point of the voltage transformers, this condition would have necessitated fully insulated transformers of increased size with larger tanks in addition to the neutral-point bushings. It is not possible to give a reliable comparison of the costs, but such an arrangement would be more expensive than the relatively simple measures required to suppress neutral inversion, as well as being difficult to accommodate in the existing switch panels. An alternative method

would be to connect the voltage transformers directly across the alternator instead of at the switchgear.

It is explained in the paper that the evidence indicated that the failures at Salt River originated in the flashover of the lead extension insulation which occurred while the machines were on load, and that neutral inversion was a contributory factor.

The main advantages claimed for hydrogen cooling, i.e. improvement in efficiency and reduction in the operating temperature of the alternator, would be obtained equally with high- and low-voltage alternators. Hydrogen has also a theoretical advantage in that the formation of oxygen compounds owing to corona would be eliminated; no difficulties due to this cause are experienced in either low- or high-voltage air-cooled machines.

Mr. Gurney is correct in stating that the concentric conductor is a voltage-grading device; and I would add that it was only the introduction of this principle, by Sir Charles Parsons and Mr. J. Rosen, which made possible the development of the high-voltage turbo-type alternator 11 or 12 years ago.* Theoretically the condenser-bushing type of conductor produces the same result, but the concentric conductor has the advantage that the voltage gradients are controlled by the potential generated in the conductors. In the condenser bushing the potentials of the conducting sheaths are determined not only by the capacitance but also by the conductance of the insulation. It is doubtful whether there is any means of ensuring that the insulation resistance of built-up mica insulation is uniform, and changes in both resistance and capacitance would take place with variations in temperature gradient. It is probable that in service the potentials of the conducting sheaths vary widely from their correct values. The conducting layers also have the disadvantage of connecting in series the weaker places in the layers of insulation, thus increasing the risk of breakdown.

As is mentioned in the paper, the concentric conductors are impregnated under high pressure during construction. The impregnation of the completed windings and the joint insulation is an additional process which has obvious advantages. The impregnating medium used is hardened on the surface by oxidation, but it also has the property of setting throughout the body of the varnish. It has the advantage that it does not become brittle, and retains a large degree of flexibility. When the alternator mentioned on page 345 was constructed it was not the practice to impregnate the complete stator. The replacement of a bar in a modern design is unlikely, but if necessary it would not be difficult to arrange for re-impregnation of the complete windings.

Mr. Atkins and Prof. Wheatcroft refer to the importance of earthing, and I am in general agreement with their views. Mr. Atkins's experience with neutral inversion is interesting.

In reply to Mr. Wall, the construction of a 66-kV generator is feasible, and in this connection the experience gained with 33-kV concentric-conductor alternators is invaluable.

It is satisfactory to have Mr. Kuyser's agreement in regard to the success of the concentric-conductor alter-

nator, but I am unable to agree that there is any better method of dealing with the problem of high-voltage generation. The only difficulty experienced with joints has been that met with at Swansea, where the load conditions have been less onerous than at Brimsdown. (Although not shown in Fig. 3, a bush is normally fitted on the outer conductor as an additional precaution.) The maximum voltage which can occur from the outer to earth is 23 kV. The insulation provided is suitable for an alternator of this voltage, and the creepage distance is ample to meet all conditions of operation. I agree with Mr. Kuyser's recommendations to earth the neutral point in order to prevent over-voltages, and particularly in order to prevent high surge voltages with the type of winding he describes. The value of the surge voltage at the neutral point is dealt with in my reply* to Dr. Kahn's contribution to the discussion.† Further surge tests have now been completed which confirm the advantages of the concentric-conductor winding, and it is hoped later to publish some of the results, including a comparison of the surge-voltage distribution with the neutral point of the alternator earthed and isolated. In the concentric-conductor winding the thickness of the insulation to earth of the outer conductor can be increased very simply and economically in order to meet over-voltages, but in a graded winding with separate conductors much of the advantage of grading is lost if the insulation thickness on the low-voltage (11 kV) winding is not kept to a minimum.

I agree that the effect of the stranded conductor is to give a theoretical increase in the potential gradient near the conductor surface of about 23 %, but the actual increase is much less. This point was investigated some time ago when dielectric-loss and breakdown tests were made which showed that there was no difference between a smooth and a stranded concentric conductor. I have referred to the condenser-bushing type of conductor in my reply to Mr. Gurney. The tests described by Mr. Kuyser on a conductor bar and joint immersed in salt water are of interest. Similar, if not more onerous, tests were made some time ago on concentric conductors and joints which were maintained for many weeks at 75 % above normal voltage in a salt-laden atmosphere of 100 % humidity at a temperature of 67° C. At the same time full-load current was passed through the bars and the temperatures were varied over a wide range in order to simulate load cycles. No signs of deterioration were observed, and the conductors and joints later withstood a pressure test of over 40 kV.

In reply to Mr. Youngmark, the method of sealing the air coolers in the foundation block at Salt River was not satisfactory and air leakage developed. In addition, difficulties experienced with the water supply to the air coolers necessitated running the alternators on the emergency open-air circuit for considerable periods. These troubles were readily overcome, and it was not found necessary to adopt any special measures such as the provision of a special inlet and filter for make-up air. Mr. Youngmark's explanation for a weakness being found in the joint of an alternator after the satisfactory experience with the first machines, is no doubt largely correct. A technique of making and insulating such

* "Direct Generation of Alternating Current at High Voltages," *Journal I.E.E.*, 1929, 67, p. 1065.

* *Journal I.E.E.*, 1940, 86, p. 364.

† *Ibid.*, 1940, 86, p. 355.

joints has been developed which is simple and reduces the danger of faulty execution to a minimum. His confirmation of the soundness of the joints from tests which he has carried out is very satisfactory.

Mr. Kidd states that 33-kV machines are reliable if the conditions on the system are satisfactory. Experience with the concentric-conductor machine shows that it is as reliable as a low-voltage design whatever the system conditions. The reactance of alternators is not a constant, and for the majority of purposes it is reasonable to assume a value of about 25 %. For a sudden short-circuit directly at the alternator terminals the sub-transient reactance is about 20 %.

I see no objection to the terminals of an alternator being arranged at the side, although I agree with Mr. Kidd that from the point of view of the layout of the foundations it is preferable for the terminals to be at one end. I am also of the opinion that the lead extensions from alternator terminals have been responsible for the formation of ozone and that it can be eliminated by correct design. It is also good practice to insulate the lead extensions, and in view of the experience at Salt River it is now customary to enclose these leads in a compartment separated from the alternator air ducts.

The efficiency of an alternator at low loads is determined mainly by the windage, friction and iron losses, and there is no appreciable difference between a high-voltage and a low-voltage design.

I agree that for neutral resistors of the liquid type a horizontal plate is a relatively poor heat-dissipator, and that electrodes in the form of vertical cylinders are to be preferred. I do not think that the material is of importance if the current density is not excessive. The high-voltage (concentric conductor) alternator is equally as suitable as a low-voltage design for operation under the conditions mentioned by Mr. Kidd.

Short-circuit tests under the conditions mentioned by Mr. Bell would not be severe. Sudden short-circuit tests at full voltage are often specified and are applied directly across the terminals of high-voltage alternators.

In reply to Mr. Carr, my experience is that high-voltage concentric-conductor alternators generate less ozone than some low-voltage machines. I have referred to lead extensions and earthing resistors in my reply to Mr. Kidd. I agree with Mr. Carr that the earthing of a system should be considered on its merits.

Replying to Mr. Sammons the phenomenon of neutral inversion is not determined by the characteristics of the machine. The soundness of the joints is confirmed by the long and satisfactory experience with concentric-conductor alternators. The improvements mentioned in the paper have further increased their reliability.

I would refer Mr. Sutcliffe to my reply to Mr. Spence on the subject of the arrangement of the voltage transformers. The first consideration is the maintenance of the principle of phase separation; one of its most important advantages is that only faults to earth can occur. The fault current is limited by the earthing resistor, and can be interrupted very easily without the danger of a more severe interphase fault developing.

The earthing resistor should be designed to suit the system protective-gear and layout. If the fault current is limited to the full-load value at normal phase voltage

the fault current at a remote point in the system may be much less. The fault current at any point must be sufficient to operate the appropriate protective apparatus.

The question of surge voltages is dealt with in my replies to Dr. Kahn and Mr. Kuyser. The distribution of capacitance in the concentric-conductor type of winding gives it inherent protection against voltage surges; no special means of protection are necessary, and none is provided for the majority of concentric-conductor alternators in service.

The list of single-conductor-type high-voltage alternators (Table A) supplied by Mr. Kilner is interesting, and his experience with the generation of ozone confirms the views I expressed in the paper.

For a direct comparison to be made between 11-kV and 33-kV alternators it is necessary that they should have similar design characteristics, the same type of winding and be similar in constructional details. While a number of tests have been made on high-voltage machines, it is difficult to meet these conditions. A comparison of the relative efficiencies of high- and low-voltage designs may be obtained from an examination of the major losses. With rotors of similar dimensions there should be no difference in the windage and the friction losses, and as the total losses are nearly equal the amounts of power absorbed by the fans should also be the same. The stator conductors of the high-voltage alternator occupy a little more space than those of the low-voltage alternator, and the volume of the teeth is greater. On the other hand, in the high-voltage machine the average tooth density is less and the iron loss in the teeth is approximately the same. In a similar manner the losses in the back of the core can be kept equal. With similar designs there is little difference in the rotor copper-losses, while the stator copper-losses are slightly reduced in the high-voltage alternator.

The stray-load losses in high-voltage alternators are of the same order as those in corresponding types of low-voltage winding. Owing to the small section of the conductors the eddy-current losses are reduced, while on account of the favourable distribution of the stator slots the rotor pole-face losses are less. Other losses are approximately equal. The total losses are slightly less in the high-voltage alternator, and it is thus more efficient than the corresponding low-voltage design, the increase being of the order of 0.1 %. It is estimated that the efficiency of a 66-kV alternator would be very little less than that of a machine wound for 33 kV, assuming that the design characteristics and other features are similar. Mr. Kilner's suggestion to insert a small reactor in the alternator neutral in conjunction with a resistor, to reduce harmonic circulating currents, should be effective.

In reply to Mr. Mellonie, the disadvantage of opening the neutral connection to interrupt a fault is that in some circumstances the fault may not be cleared, with the result that the potential in the other lines is raised to 73 % above normal to earth, and more faults may occur.

The relative dispositions of reactance in the high-voltage alternator and in the low-voltage alternator with transformer, is not likely to have a large effect upon stability, although theory and experience indicate that the former has a slight advantage.

TESTING-STATION DESIGN AND ORGANIZATION FOR THE SMALLER UNDERTAKINGS UNDER THE ELECTRICITY SUPPLY (METERS) ACT, 1936*

By E. JACKS, Graduate.†

(ABSTRACT of Paper read before the NORTH-WESTERN STUDENTS' SECTION, 13th February, 1940.)

The introduction of the Electricity Supply (Meters) Act, 1936, has caused wholesale changes to be made in the testing organization of many supply authorities and has raised many problems for the testing engineer. This paper is a study of the layout and operation of a certain testing station serving an industrial area of about 20 000 consumers.

THE METERS ACT OF 1936

The provisions of the Act are now predominant in testing station design. The specifications for the apparatus used in testing, the methods of testing, and the limits of error for meters used on public supply are all laid down in the Act. Three methods of testing are allowed, and the merits of one over another are distinct for various circumstances. Valuable flexibility of organization can be achieved if provision is made for all three methods, and this is to be advocated.

2.5 % fast to 3.5 % slow are the limits of error specified for meters on circuit, and the meters must conform to these under all conditions of service. To comply with this requirement and because of economic considerations, the testing limits must obviously be much less tolerant. The standards of accuracy depend to a great extent on the personal element, and this should receive due consideration.

Besides the range of speed and dial tests on meters, which may or may not be considered adequate, several other tests are necessary and must be accounted for in the design of the testing station. The question of tests of experimental and miscellaneous character must also be borne in mind.

ESTABLISHMENT

The testing station consists of: Test room, standardizing room, meter stores, offices, repair shops. Although the layout is a re-adaptation of existing premises, the space proportions indicated in Fig. 1 have proved successful in regard to both efficiency and economy.

The chief factors governing the layout are (as would apply also to new premises): (1) Efficient utilization of natural light. (2) Facility for the systematic handling of meters. (3) Building construction. (4) Spacing of gear. (5) Methods of testing. (6) General appearance.

Good lighting is essential to accuracy, and natural light should be utilized to the full but without subjecting the more delicate instruments to direct sunlight. Windows of a north aspect, where possible, are a very

desirable solution of the problem. Artificial lighting in the test room under consideration is general, and the average illumination at any point is 16 to 18 foot-candles.

The "flow" of meters inwards and outwards through stores and test-room is systematically effected, and the

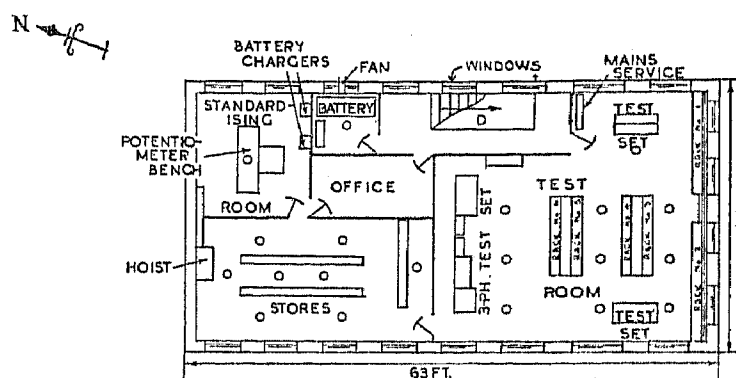


Fig. 1.—Layout of testing department, including lighting plan.

steel storage racks are sectionalized so as to accommodate meters in the various stages of progress.

In considering the design of an entirely new establishment, it is most desirable that the architect and engineer should work together, but it is in the equipping of an existing building that the reason for such co-operation becomes apparent. Solid foundations to prevent vibration, ducts to carry interconnecting cables, and many other points, require early attention.

THE TEST-ROOM

Fig. 1 shows that ample working space has been provided; all three methods of testing are catered for, and each piece of apparatus stands out as an independent feature. This spacing has necessitated a high degree of finish for each item and lends itself to cleanliness and accessibility, points which are indispensable to accuracy and efficiency.

All meter racks are interconnected with all test sets, so that any set may feed any number of racks in series. Cables running in asbestos-lined ducts are of liberal section, so that the voltage drop between instruments and meters under test is negligible. Conduit and other ironwork has been avoided where possible, in order to minimize stray-field effects. Connections are mostly sweated, and contacts are big enough for easy cleaning.

Steady voltage and good wave-shape are the essential features of the mains supply, which is taken from a substation within the premises. Most of the gear has

* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

† Leigh Corporation Electric Supply.

been made by the departmental staff, and it is to this part of it that the following descriptions mainly apply.

THE TEST SETS

Meters on test are run by "phantom" load, i.e. the rated voltage is applied to the voltage coil and a low voltage across the series coil to circulate the required

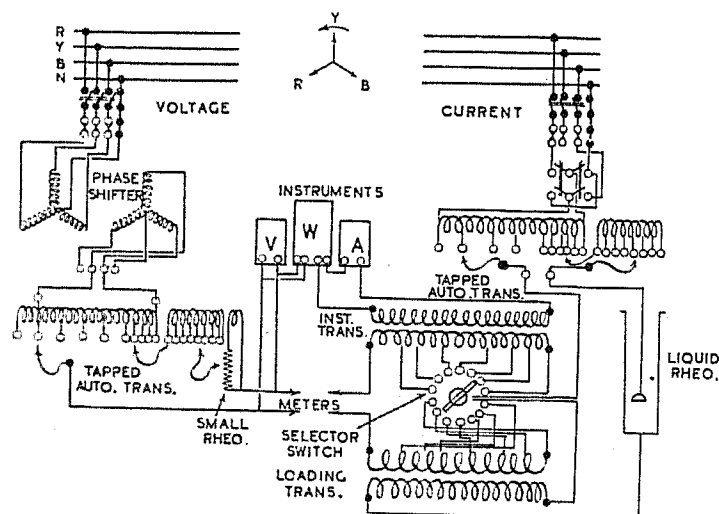


Fig. 2.—Diagram of test set for Method C.

current. A means of varying the phase angle between current and voltage is, of course, necessary to supply loads of different power factors and to compensate for the internal reactance of the meters.

Fig. 2 is a circuit diagram of the single-phase set used for the method referred to in the Meters Act as

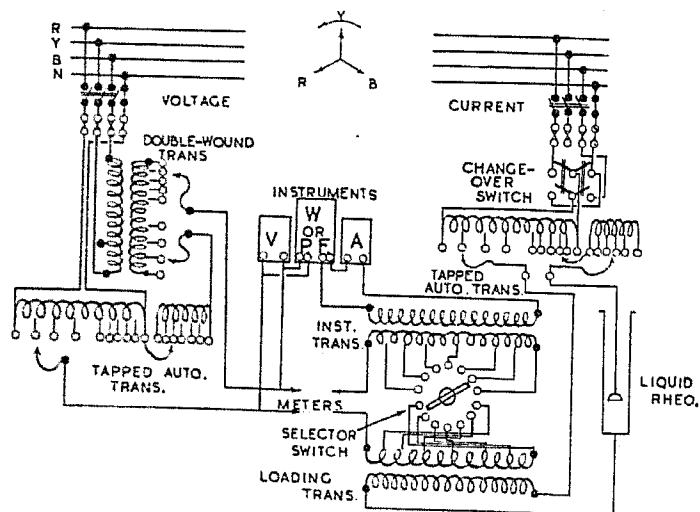


Fig. 3.—Diagram of test set for Method A.

Method C. The voltage and current are infinitely variable over the ranges 0-500 volts and 0.1-100 amp. The phase-shifter is an old-type 7-h.p. induction motor with suitable characteristics; its secondary voltage is smooth,

it is noiseless in operation and is fitted to respond to the handwheel without backlash. A quick change from 1.0 p.f. to 0.5 p.f. lagging can be made by means of the change-over switch shown in the diagram. Another feature is the liquid rheostat, which ensures smooth control, absolutely free from backlash.

The test set for Method A (Fig. 3) is similar in principle to that for Method C, but differs in regard to the method of phase-shifting and in appearance. This set is used in conjunction with a substandard rotating meter. The predominant factor in the design of these sets is ease of control and facility for speedy load-setting. The transformers used are of 5 kVA standard rating but are used at low flux density to ensure good wave-shape.

The six testing racks, made to hold some 30 meters each, are of special design, and form integral features of the test room.

A pendulum clock together with a wireless set for receiving a daily time signal, are employed as a time standard in accordance with the provisions of the Act.

THE STANDARDIZING ROOM

Only a detailed description could do justice to this all-important section, but Fig. 4 illustrates the layout

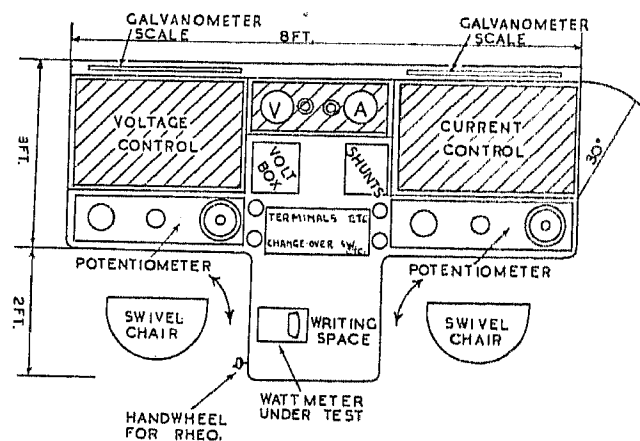


Fig. 4.—Layout of potentiometer bench.

by which ease of control and accessibility of components has been achieved. No effort has been spared to attain the highest standards of contact, insulation and mechanical stability.

TESTING CAPACITY

To allow for possible future extension and abnormalities of demand, a monthly output of about 500 meters has been catered for. This figure is, of course, dependent on staff organization, and could be improved upon should the occasion arise.

DISCUSSION ON "AN IMPROVED CELL FOR THE A.C. AND D.C. TESTING OF INSULATING OILS"*

Mr. J. K. Webb (*communicated*): An examination of the design of the oil testing-cell proposed by Dr. Bramley reminds me of a classical controversy between Lord Lister and Dr. Bennett, whose experiments apparently showed that microbes arose *de novo*. Lister perceived that by too strict an adherence to certain academic aspects of the problem, Bennett's apparatus had become over-complicated, with the result that the all-important question of absolute cleanliness had been overlooked. I am afraid that the present design is open to the same criticism. There are so many nooks and crannies where the "germs" of power factor may lurk that even in skilled hands much appears to depend on the personal factor and the skill and care devoted to securing effective cleaning. This is tacitly admitted by the author in his paragraph on "Setting up the Cell for Test (Empty)."

Now very great simplification is possible if the guard circuit is eliminated, and it may be of interest to refer to such a two-terminal type of cell which, although entrusted to junior test assistants, gives reproducible and consistent results as judged from various cross-checks taken over a period of some years with six similar cells distributed between three separate works' testing departments. Speed, ease and reliability are desirable where a large volume of testing has to be handled, and the errors which arise through the omission of screens are quite negligible compared with those which can so easily be introduced by contamination of the sample.

The design which I adopted was placed at my disposal about four years ago by the National Physical Laboratory, and has since been described by Dr. Hartshorn and Mr. Rushton.†

To suit the particular requirements of factory testing, a modified form as illustrated in Fig. A was constructed.‡ The provision of the electric heater is an added convenience. It has not usually been found essential to fill the cell under vacuum, and the nipples F simply serve as overflows as the inner electrode assembly is lowered into the outer case in which the test sample has been placed.

A thermometer may be inserted into the body of the cell, and a power-factor/temperature curve quickly obtained by heating to 110° C. and taking measurements during cooling, the cell being left in the heater, which has been disconnected from the mains. The temperatures so recorded are very close to the actual temperature of the oil film on account of the high thermal conductance of the solid electrode. While the condition of an insulating oil may most easily be determined by means of the test cell from measurements made at 50 c./s., the cell may also be used for d.c. measurements, and it is,

moreover, particularly suitable for tests at very high frequencies.

The problem of contamination becomes even more acute in the case of measurements made on good solvents such as benzene and monomeric styrene, and experience has shown that a cell of the simple type now described is, on account of ease of cleaning, well adapted for this purpose. It would therefore seem, on the whole, to represent a neater solution of the problem and a better compromise between the various contending factors than the one advanced by Dr. Bramley.

Dr. L. N. Bramley (*in reply*): Replying to the criticism of Mr. Webb, I would point out that the requirements of design of an ideal test-cell as set out in the paper are accepted by the great majority of workers in this field, and ample proof of their correctness may be seen in the American literature on the subject, which has been for several years notably in advance of our own.

A study of the cell used by Mr. Webb appears to show that, of the essential requirements mentioned in my paper, (1), (2) and (3) have been sacrificed for the sake of simplicity. These points are dealt with below.

Dealing with (1) and (2), namely negligible dielectric-loss angle and efficient guarding and screening, the presence of quartz in the low-voltage—high-voltage field precludes the possibility of the cell ever showing zero dielectric-loss angle. The actual loss angle may be small, but, in measurements on the new liquid dielectrics now being developed, its effect may be appreciable. As was mentioned by Dr. Hartshorn and Mr. Rushton in their paper,† a correction must sometimes be applied for the dielectric-loss angle of the quartz washer. This should never be necessary, however, when using a correctly designed three-electrode cell such as the one described.

As regards requirement (3), namely uniformity of stress, Mr. Webb's diagram indicates that the length of the oil-gap at the base of the cell is several times that of the cylindrical gap, so that the stress on the oil varies over wide limits. No oils other than those with flat dielectric-loss angle/stress curves can thus be assessed in the cell without error, and such oils appear to be rare. The achievement and maintenance of a uniform gap is therefore an important matter. It would be interesting to compare the uniformity of the gap preserved by the taper surfaces of the two-electrode cell with that of the screened cell, which is located at both ends of the cylindrical portion of the gap.

Turning now to requirement (6), robustness, the delicate conical quartz washer used in the cell described by Mr. Webb can hardly be described as robust. Spares of this part, which would undoubtedly be expensive, would have to be carried, as they could not be easily

* Paper by Dr. L. N. BRAMLEY (see 86, p. 326).

† L. HARTSHORN and E. RUSHTON: "A Condenser for the Testing of Liquid Dielectrics," *Journal of Scientific Instruments*, 1939, 16, p. 366.

‡ I am indebted to Messrs. Standard Telephones and Cables, Ltd., for permission to publish these particulars.

† *Loc cit.*

or quickly obtained. The effects of one particle of dirt or grit on the quartz surface can well be imagined, so that the operations of cleaning and assembly cannot be described as simple and certain. Incidentally, in the published description of this cell, it is specified that the

of 80° C. is extremely large in many liquid dielectrics, and an error of even 1 deg. C. has an appreciable effect at this temperature. In this connection, the adaptation of the screened cell described in the paper to deep immersion in an oil bath allows a series of steady temperatures to be

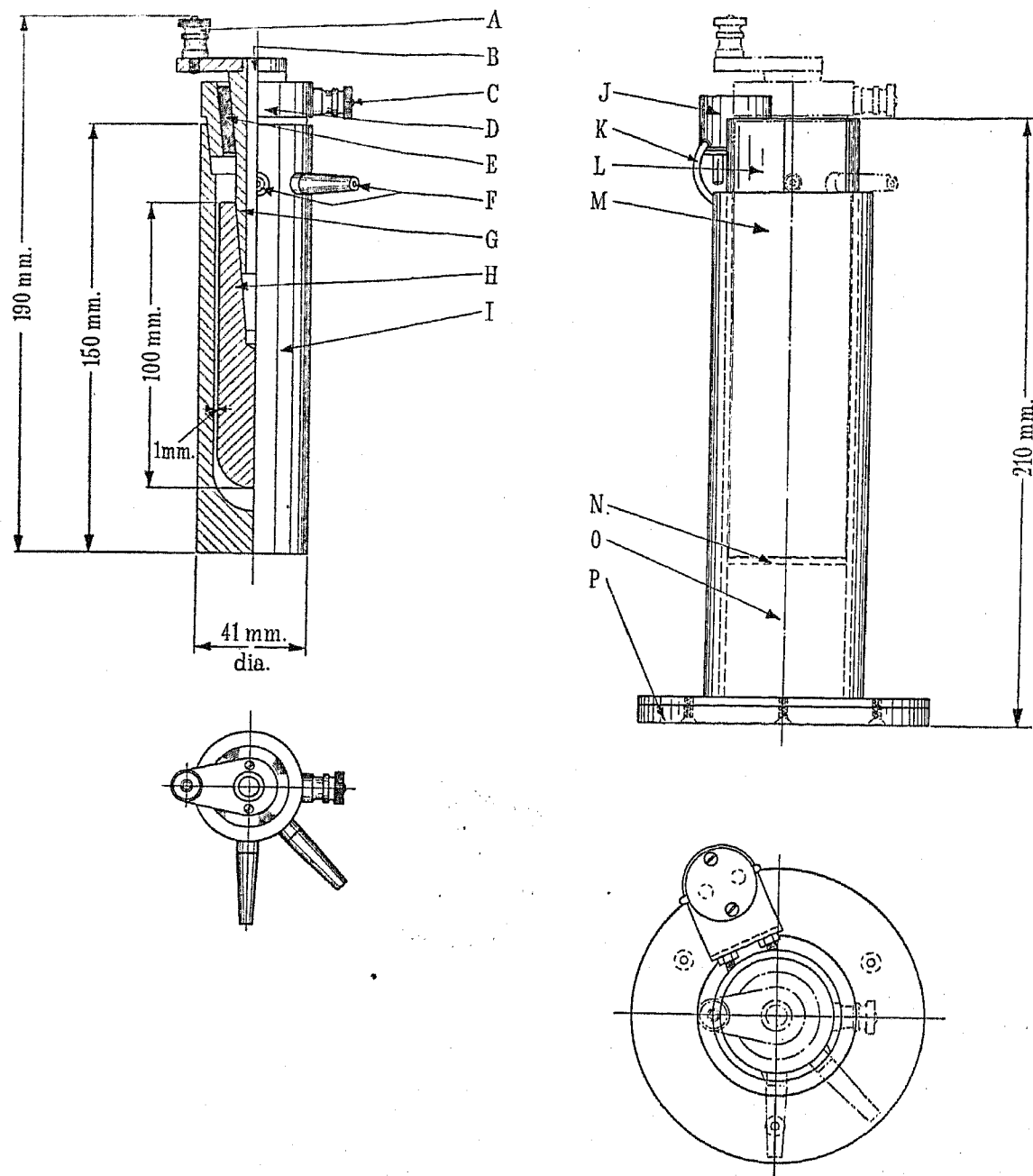


Fig. A.—Test cell and heater.

- A. Terminal for connection to low-voltage inner electrode.
- B. Hole to take 7-mm. diameter thermometer.
- C. Terminal for high-voltage outer electrode comprising case.
- D. Conically-ground piece to maintain quartz washer in position.
- E. Quartz washer, top and bottom faces polished. (The washer need not normally be dismantled from D and G.)
- F. Evacuating and filling nipples, ground to standard No. A7 taper.
- G. Hollow conically-ground centring-piece.
- H. Low-voltage electrode held by friction grip to conical surface of item G. (The electrode is easy to remove for cleaning, and one of different size may be substituted if desired.)
- I. Outer electrode and case (connected to source of high potential—usually about 400 volts).

- J. Terminal block.
- K. Insulated wire from terminal block.
- L. Brass tube in which cell is a loose sliding fit.
- M. Electrical lagging and insulation wound to a resistance of about 500 ohms.
- N. Seat for cell.
- O. False bottom filled with mica dust.
- P. Hard asbestos sheet screwed to brass disc.

Material of cell: Invar, rhodium-plated.
Capacitance empty (1-mm. gap), 94 $\mu\mu\text{F}$.
Volume of sample required, 16 cm^3

main body should be made of Invar, in order to avoid fracturing the quartz washer in the course of temperature changes.

In regard to precise temperature control, requirement (7), the importance of obtaining and maintaining an even temperature over the test portion of the cell was stressed in the paper, but the cell described by Mr. Webb appears to be subject to an error of this kind. The rise in dielectric-loss angle with temperature in the region

quickly obtained over the range desired, and thus does away with the great practical difficulties associated with the measurement of temperature and the balancing of the dielectric-loss-angle bridge under conditions such as Mr. Webb's when the heating circuit is presumably disconnected and the temperature is falling. Incidentally, with the oil-bath method six oil characteristics can be measured simultaneously in little more time than it takes to measure one. This would not seem to be

possible with a batch of cells such as is described by Mr. Webb.

The criteria of cheapness and ease of construction might well have been added to the requirements set out in the paper, and it would appear that here again the guarded and screened cell has a considerable advantage. As is shown in the paper, this type of cell can be very simply and easily constructed of brass and mycalex in a small workshop, whereas the provision of quartz and Invar components in the two-electrode cell would greatly restrict manufacture. It is thus apparent, from considerations alike of manufacture and of materials, that the cost of the cell advocated by Mr. Webb must be many times that of the screened and guarded cell described.

In regard to the cleaning of the upper guard of the screened cell, no difficulty has been experienced during some three years of operation of a bath containing six such cells and no "germs" of power factor have yet been found.

In conclusion, I must say that my experience completely justifies the contention of other workers regarding the necessity for the refinements which Mr. Webb would abandon. Moreover, his simplification is of little practical importance and is not justified in view of the risk of errors which it introduces. It would appear that the problem of deciding the best form of cell for the measurement of dielectric-loss angle of insulating oils has become so important as to justify examination and standardization by the British Standards Institution.

DISCUSSION ON "THE THEORY OF THE THERMIONIC DIODE"*

Dr. E. B. Moullin (*communicated*): Even the simplest analysis of the cylindrical diode is peculiarly troublesome to reduce to a form suitable for numerical computation, and it is a remarkable achievement on the part of the author to have ground out a numerical solution for velocity-distributed electrons. Langmuir has reduced the solution for the planar case to a simple numerical form; this is clearly impossible for the much more complicated cylindrical case. Nevertheless, I have been tempted to try to reduce the extreme case of the cylinder to a form which admits of simple comparison with the planar case. The case of greatest interest is when I/I_0 is small, for then there is likely to be most discrepancy between the cylindrical and the planar system. Moreover, it will be helpful in discussing the behaviour of a triode with very negative grid, where we wish to know whether the barrier has advanced up to the grid surface. It is necessary first to evaluate probable values for the parameter

$$B_0 = \frac{6.69 \times 10^{10} I_0 r_0}{\tau^{\frac{2}{3}} l} = \frac{42.1 \times 10^{10} r_0^2}{\tau^{\frac{2}{3}}} \times (\text{Current per unit area})$$

Taking an emission current of 0.3 amp. per cm² at temperatures of 2500° K., 1900° K., and 1000° K. for tungsten, thoriated tungsten and oxide cathodes respectively gives $B_0 = 10^6 r_0^2$, $1.55 \times 10^6 r_0^2$ and $4 \times 10^6 r_0^2$ respectively. Now taking $r_0 = 0.1$ mm. and 0.5 mm. for tungsten filaments and coated cathodes respectively gives B_0 equal to 100, 155 and 10 000 respectively for tungsten, thoriated-tungsten or coated cathodes. Hence at normal working temperatures we are concerned with values of B_0 greater than 100. Now confine attention to I_0/I greater than, say, 52, for which $\log I_0/I$ is greater

than 4. Reference to Fig. 3 shows that then the relation between w_m and $\log I_0/I$ is linear and almost independent of B_0 , and is given by

$$w_m = 0.77 + 1.06 \log (I_0/I)$$

or

$$I/I_0 = 2e^{-w_m/1.06}$$

For a planar cathode, $w'_m = \log (I_0/I)$

$$\begin{aligned} \therefore \frac{w_m}{w'_m} &= 1.06 + \frac{0.77}{\log I_0/I} \\ &= 1.25 \quad \text{if } I_0/I = 52 \\ \text{or} \quad &= 1.14 \quad \text{if } I_0/I = 10^4 \end{aligned}$$

Thus the cylindrical system increases the negative potential at the barrier by about 20 %: it is as though the emission were doubled and the temperature increased by 6 %. The slope resistance of the cathode-barrier region is an important parameter in Schottky's theory of space-charge reduction of shot effect: it follows that, with cylindrical electrodes,

$$\frac{dI}{dV} = \frac{1}{\rho'} = \frac{eI}{1.06k\tau}$$

Now to compare the barrier distance with that for the planar case and confine attention to I_0/I greater than 1000, then for plain or thoriated tungsten $\log_e B$ exceeds -1.87 . Reference to Fig. 2(a) shows that if $\log_e B$ exceeds -2 ,

$$\begin{aligned} \log (r_m/r_0) &= 0.9 - 0.75 \log_e B \\ \therefore r_m/r_0 &= 2.46 B^{-\frac{1}{4}} \\ \text{or } (r_m/r_0)^{\frac{1}{4}} B &= 3.32 \end{aligned}$$

which is

$$\left(\frac{r_m}{r_0}\right)^{\frac{1}{4}} \times 4\pi \left(\frac{m}{2e}\right)^{\frac{1}{2}} r_0^2 \times (\text{Current per unit area}) = \frac{6.64}{2\sqrt{\pi}} \left(\frac{kT}{e}\right)^{\frac{1}{2}}$$

* Paper by Prof. E. L. E. WHEATCROFT (see 86, p. 473).

If x_m is the distance from a plane cathode to the barrier, then*

$$4\pi\left(\frac{m}{2e}\right)^{\frac{1}{2}}x_m^2 \times \text{Current per unit area} = \frac{\psi_0^2}{2\sqrt{\pi}}\left(\frac{kT}{e}\right)^{\frac{1}{2}}$$

$$\therefore \left(\frac{r_m}{r_0}\right)^{\frac{3}{2}} \frac{r_0^2}{x_m^2} = \frac{6.64}{\psi_0^2}$$

Values of ψ_0^2 have been tabulated by Langmuir; ψ_0^2 is equal to 6.35 when $I_0/I = 1000$ and is equal to 6.56 when $I_0/I = \infty$. Hence $r_m/r_0 \simeq (x_m/r_0)^{\frac{2}{3}}$.

$$\text{Now } x_m = \frac{1}{320I^{\frac{1}{2}}}\left(\frac{kT}{e}\right)^{\frac{1}{2}}$$

$$= 10^{-3}I^{-\frac{1}{2}} \quad \text{if } T = 2500^\circ \text{ K.}$$

$$\text{or } = \frac{1}{1.24 \times 10^3 I^{\frac{1}{2}}} \quad \text{if } T = 1900^\circ \text{ K.}$$

then $\log(r_m/r_0) = 1.3$, or $r_m/r_0 = 3.67$; and thus $(r_m - r_0) = 1.33 \text{ mm.}$ When $T = 1000$, $x_m = (1/2000)I^{\frac{1}{2}} = 0.9 \text{ mm.}$, if $I = 30 \mu\text{A per cm}^2$. So now the cathode-to-barrier distance is 45 % greater than for the planar system. We may summarize the results as follows: For oxide-coated cathodes I/I_0 must be less than 10^{-3} before the cathode-to-barrier distance is 50 % greater than for the planar case. For hot thin cathodes, $r_m \simeq x_m$ when $I/I_0 > 10^{-2}$; and $r_m/r_0 = (x_m/r_0)^{\frac{2}{3}}$ when I/I_0 is less than 10^{-3} .

For triodes with coated cathodes the barrier will in general have reached the grid surface before $I/I_0 = 10^{-3}$, and for thin cathodes it will not have reached it until $I/I_0 \simeq 1/4000$.

It would be a very valuable addition to the paper if the author could derive the force/distance curve in the barrier region for one or two typical cases. Then it

Table A

ξ	w for $B_0 = 1$					w for $B_0 = 16$							w for $B_0 = 256$				
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.25	0.75	0.73	0.62	0.54	0.39	1.74	1.73	1.72	1.71	1.70	1.52	1.31	3.60	3.60	3.58	3.55	3.50
0.5	1.42	1.33	1.14	1.00	0.68	2.92	2.85	2.80	2.76	2.72	2.42	1.90	5.22	5.22	5.20	4.93	4.61
0.75	1.98	1.87	1.60	1.38	0.87	3.86	3.79	3.70	3.56	3.38	2.86		6.26	6.25	6.20	5.68	4.98
1.0	2.50	2.38	2.00	1.69	0.98	4.60	4.51	4.35	4.16	3.75	3.00		7.19	7.12	6.88	5.97	
1.25	2.96	2.82	2.31	1.88		5.23	5.08	4.87	4.56	3.95			7.89	7.80	7.40		
1.5	3.39	3.23	2.57	1.97		5.75	5.53	5.26	4.84				8.47	8.34	7.73		
1.75	3.79	3.59	2.77			6.20	5.96	5.58	4.98				8.97	8.80	7.92		
2.0	4.15	3.92	2.91			6.58	6.32	5.80					9.43	9.18	8.00		
2.25	4.48	4.19	2.99			6.93	6.56	5.95					9.83	9.50			
2.5	4.78	4.41				7.23	6.77	5.99					10.14	9.74			
2.75	5.04	4.60				7.49	6.90						10.40	9.89			
3.0	5.28	4.76				7.70	6.98						10.62	9.98			
3.25	5.48	4.89				7.85							10.79	10.00			
3.5	5.66	4.96				7.95							10.92				
3.75	5.80	5.00				7.99							10.98				
4.0	5.91																
4.25	5.97																
4.5	6.00																
w_m	6	5	3	2	1	8	7	6	5	4	3	2	11	10	8	6	5
ξ_m	4.52	3.78	2.39	1.73	1.15	3.86	3.17	2.53	1.93	1.45	1.00	0.72	3.90	3.25	2.03	1.12	0.80
$\log I_0/I$	4.91	3.99	2.20	1.36	0.59	6.77	5.84	4.93	4.02	3.11	2.28	1.53	9.63	8.69	6.83	5.10	4.37

Hence if $I = 0.3 \text{ mA per cm}^2$, x_m is of the order of 0.05 cm. Then if $r_0 = 0.1 \text{ mm.}$, $r_m/r_0 = 5^{\frac{2}{3}} = 11.4$,

$$\therefore r_m = 1.14 \text{ mm.}$$

Hence with this current from a thin filament the barrier would not have reached the grid surface of a triode: if $I = 30 \mu\text{A per cm}^2$ then $r_m = 6.4 \text{ mm.}$, and in general the barrier would have reached the grid and the analysis would no longer be valid. It would seem that for hot thin cathodes at normal temperatures the barrier will be between grid and cathode so long as the current is greater than $1/4000$ of the emission, and then the potential of the barrier will be about -2.2 volts.

For oxide-coated cathodes, $I_0/I = 1000$ makes $B = 10$, and this is outside the range in which our empirical relation is valid. Reference to Fig. 2(b) shows that

would be possible to calculate the transit time from cathode to barrier. Also, I think it would then be possible to check Schottky's solution for the retarding field, at any rate in certain specified cases. This might throw some light on the anomalous cathode temperatures which sometimes are derived from the slope of the retarding-field characteristic. At least the author has now made it possible for us to calculate whether or not a barrier exists when the anode is negative to the cathode and the emission is known.

I think a little more explanation is required of Figs. 4, 5 and 6. In these curves the ordinates are the product Cw and yet the bounding curve is for $C = 0$; evidently when C tends to zero the product Cw tends to some finite value, but I do not see how this comes about.

Prof. E. L. E. Wheatcroft (in reply): It is gratifying that Dr. Moullin has found time to contribute such an

* See E. L. E. WHEATCROFT: "Gaseous Electrical Conductors" (Oxford, 1938), p. 73

interesting communication. To take the last paragraph first, I do not think there is any doubt that Cw is finite as C approaches zero. From equation (3c) of the paper, C may be zero either because τ is zero or because I_0 is infinite. In the first case Cw is independent of τ , and the second can be considered as follows: If I_0 is infinite we know from the solution of Langmuir's equation that V will be infinite even for small finite values of ξ ; Cw is again, therefore, finite because w becomes infinite.

Figs. 2 and 3 of the paper are based on 17 calculated solutions of equation (8) by the methods of Appendix 2. These solutions are given here in Table A. For the 17 selected cases it will be possible to calculate the velocity at any radius for any given initial velocities. It is probable, however, that for practical use some "average" time of transit will be needed, and for that purpose I have endeavoured to estimate $\frac{1}{I} \int tdI$, where the integration covers those electrons which reach the anode.

From equations (4) and (5) it can be shown that

$$\int tdI = \frac{I_0}{\sqrt{\pi}u_\tau} \int S' dr$$

where $S' = 2\sqrt{\pi}e^{-w} \int_0^\infty (1 - \operatorname{erf} p)e^{(\eta-1)wy} d\sqrt{wy}$

and p^2 is defined in Fig. 7.

For $p < p_0$ we have

$$(1 - \operatorname{erf} p) > (1 - \operatorname{erf} p_0)e^{p_0^2 - p^2} < e^{-p^2}$$

These two limiting approximations give, for $\frac{1}{I} \int tdI$, alternatively

$$\frac{\sqrt{\pi}}{u_\tau} \int f(p_0^2) dr \quad \text{and} \quad \frac{\sqrt{\pi}}{u_\tau} \int dr$$

Integrating these two solutions for typical cases we get, for the "average" time from cathode to minimum surface,

$$1.1d_m/u_\tau \quad \text{and} \quad 1.6d_m/u_\tau$$

where $d_m = r_m - r_0$ as before, the results being apparently independent of I_0 and I .

It is unfortunate that the two approximations do not come closer together. However, in default of more accurate calculation, we may assume that the value $1.35d_m/u_\tau$ is certainly correct to within 20 %, and probably to within 10 %.

For the region of accelerating field the approximation of Appendix 4 and equation (23) is quite close to the truth, i.e.

$$\begin{aligned} & \frac{\sqrt{\pi}}{u_\tau} \int_{r_m}^{r_a} f(w') dr \\ &= \frac{\sqrt{\pi}r_m}{u_\tau} \int_0^\xi f(w') e^{\xi} d\xi \\ &= \frac{\sqrt{\pi}r_m}{u_\tau B_m} \left[\frac{dw}{d\xi} \right] \end{aligned}$$

where the term in the square bracket can be found from Fig. 6.

It must be remembered that, as is stated in Section (2) (top of page 475) of the paper, the solutions given do not apply to the cases where there is no minimum surface between cathode and anode.

There are two small printer's errors in the paper. Equation (8) is correctly given on page 478 and incorrectly on page 481. Also, the equation at the foot of page 483 should read $p_0^2 = w' = w_m - w$.

DISCUSSION ON

"THE SECONDARY CIRCUITS OF SYNCHRONOUS INDUCTION MOTORS"*

Mr. E. Barraclough (*communicated*): Referring to Section 3(a) of the paper, I suggest that the claim "that the excitation varies automatically with load" is not quite correct. In the system described the excitation is obviously a function of the line current, which in turn is affected directly by (1) line voltage, (2) load, (3) power factor. It is therefore obvious that if owing to mechanical or electrical disturbances a slightly extra line current is taken by a motor controlled in the manner described, the excitation will increase, thereby altering the power factor, which in turn will again increase the excitation since the initial change causes a greater line current to flow.

In Section 3(c) it is stated that "A quiet machine especially will require to have a sinusoidally distributed secondary." Machines manufactured at the present time usually have their iron parts working at high magnetic densities. This results in a flux wave having a maximum

value often 20 % less than the maximum value of a sine wave having equal area. From many points of view this flattening of the flux wave is extremely advantageous. On the other hand a machine having such a flattened flux wave-form can be, and often is, made which is very quiet in operation. I doubt whether any modern commercial machine of the synchronous induction-motor type would be capable of generating a sine wave, although experience has shown that such machines are sufficiently quiet.

In Section 3(g) it is mentioned that "All windings, except the fundamental methods 1-7 (Table 1), share the disadvantage that if the exciter fails the whole set is out of commission and cannot be run as an induction motor." Referring to method No. 12, Table 1, a motor wound in accordance with this principle is capable of running continuously on full load as an induction motor, with or without the exciter in circuit. From the nature of the winding it is evident, however, that the heating of the

* Paper by Mr. G. H. RAWCLIFFE (see 87, p. 282).

secondary circuit must be uneven, since one phase has a higher resistance than the other two. On the other hand, the secondary winding of a synchronous induction motor would contain very much more copper than would the secondary winding of a similarly rated induction motor. The consequence of this is that whilst operating as an induction motor the secondary winding of a synchronous induction motor is not heated to anything approaching the same extent.

In addition to this it should be appreciated that such windings, composed as they are of rectangular copper insulated by hot-pressed mica, have a very small temperature gradient between the copper and the iron in which they are embedded. Consequently the temperature rise of this high-resistance phase is much lower than would at first sight be anticipated. Experience has proved that such motors are capable of running without trouble for as long a period as 6 months when operating very heavy drives calling for high over-load torques.

Mr. L. J. Hunt (*communicated*): I notice that the author refers to my paper on "The Cascade Induction Motor,"* and in this connection I should like to explain that it is only the rotor winding, shown in Fig. 10 of this paper, that is used in the synchronous type of machine. The current flowing in this winding is capable of producing two numbers of poles in the ratio of 1 to 2, and so couples in cascade the d.c. and a.c. elements of the machine. The stator winding generally consists of two parallel-connected star windings, to the terminals of which are connected the a.c. mains, the exciter being connected between the neutral points. The alternating and direct currents flow in the same windings, but produce different numbers of poles. The construction of these machines and their windings has been fully described elsewhere.

It may be of interest to mention that these machines when driven as alternators are self-paralleling, and will run satisfactorily in parallel when driven by engines with large cyclic irregularity.†

F. Creedy, in a paper‡ read before The Institution in 1921, showed that the type of rotor winding to which reference has already been made can be adapted to suit any number of poles, and the machine described by Prof. Schenfer (British Patent No. 231642) is of the same type, but was not previously used because of the difficulty of keeping out of the mains the currents induced by the second field. Prof. Schenfer has provided means for preventing currents of line frequency from flowing through the exciter, but not for keeping out of these

windings the currents of lower frequency induced whilst the machine is running up to speed.

Mr. G. H. Rawcliffe (*in reply*): I agree with Mr. Barraclough that the statement that the excitation varies "automatically with load" is just a little loose; "automatically with load current" would perhaps be better. On the other hand the object of the system of variable automatic excitation is to vary the excitation at just such a rate that the power factor will be sensibly constant, in which case the load current and load are directly proportional, neglecting fluctuations in line voltage, which are normally negligible.

The highest possible magnetic loadings, to increase the ratings of machines to their maximum, are of course not consonant with sine waves of flux. It would probably be more correct to say that, all other things being equal, a sinusoidal secondary *flux*, rather than m.m.f., is desirable, as nearly as is consistent with a commercially practicable magnetic loading. Undoubtedly the desire for increased rating has of late years obtained pride of place over the desire for sine wave-forms. Noise is an exceedingly complicated question, and though quiet machines may be made having non-sinusoidal wave-forms, it still seems likely that, all other things being the same, sine wave-forms would give more silent operation.

When considering induction overload capacity there are three possibilities: (a) Inadequate induction torque, and certainly also overheating if the induction action is long sustained. (b) Adequate induction torque, but overheating on prolonged induction operation. (c) Adequate induction torque capable of being prolonged indefinitely; thus permitting the set to be run as an induction motor, without exciter, if the latter becomes faulty.

I had imagined that the method of excitation referred to as No. 12 in Table I came under (b), but I accept with interest the statement that it in fact comes under (c). That it does so is an illustration of the remarks in Section 3(b) of the paper, about the distribution of heating in the secondary, which Mr. Barraclough himself confirms.

In reply to Mr. Hunt, I had hardly wished to do more than indicate, in passing, that the synchronous induction principle could be extended to cascade motors; but it is certainly worth recording that the stator arrangement may differ when this is done, though for a "2-machine" cascade motor of the fundamental type this would not be so. It may be recorded that a "2-machine" cascade *induction* motor, of the fundamental type, cascaded stator-rotor-rotor-stator, for driving live rolls in steelworks, not long ago made its reappearance; the object being to secure a long narrow machine, of minimum inertia, but with 16 poles.

* *Journal I.E.E.*, 1914, 52, p. 406.

† *Electrical Review*, 1925, 96, p. 766. ‡ *Journal I.E.E.*, 1921, 59, p. 511.

INSTITUTION NOTES

ROLL OF HONOUR (FOURTH LIST)*

Killed in Action.

McKee, Sergeant J.	Royal Air Force	Student
Powell, Lance-Sergeant G.	Royal Signals	Student

Killed on Active Service.

McVicar, Major J.	Royal Army Ordnance Corps	Associate Member
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HONOURS AWARDED TO MEMBERS SERVING WITH H.M. FORCES (THIRD LIST)†

O.B.E.

Brazier, Lieut.-Col. C. C. H.	Royal Engineers	Associate Member
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Mentioned in Despatches.

Ball, Sub-Lieut. C. E.	Royal Naval Volunteer Reserve	Student
Stott, Captain J.	Royal Army Service Corps	Graduate

PAGE PRIZE

The Council have awarded the Page Prize for 1939-40 (value approximately £5) to Mr. H. G. Dennes for his thesis entitled "The Conversion of a 1250-kVA Hydro-electric Generating Plant to Semi-Automatic Operation."

ORDINARY MEETING, THURSDAY, 2nd JANUARY, 1941, AT 12.30 p.m.

In order to comply with the Bye-laws a formal Ordinary Meeting of The Institution will be held on the above date for the suspension of a list of applicants for election and transfer approved by the Council for ballot.

ARRANGEMENTS FOR THE SECOND HALF OF THE SESSION

The Council have decided that under prevailing conditions it would be inadvisable to hold meetings of The Institution in London during the second half of the session. Particulars of the papers that would have been included in the programme will be published in the January issue of Part I of the *Journal* so that applications for advance copies can be made to the Secretary at the appropriate time by those members who contemplate the submission of written contributions for publication, in the form of discussion, in the *Journal*.

INDEX TO JOURNAL

Any member who proposes to bind the current volume of the *Journal* and would like to have an extra copy of the Index for filing apart from the bound volume of the *Journal* can obtain an additional copy on application to the Secretary.

* See *Journal I.E.E.*, 86, p. 510 and 87, pp. 110 and 351.
† See *Journal I.E.E.*, 86, p. 510, and 87, p. 351.

CENTRAL REGISTER OF NATIONAL SERVICE

The following summary shows the number of members enrolled in the Register and the number of vacancies for which orders had been received up to 16th October:—

Number of members eligible for enrolment in the Register		12 486
Number enrolled		11 866
Number of orders received		267
Vacancies represented by above orders		937
Names put forward for above vacancies		3 816
Confirmation of appointments received (to September, 1940)		547
Students enrolled in the Subsidiary Register (now called the Junior Register)		380

The Secretary of The Institution would be glad if all members who volunteered, and also those members who sent in their red cards for record purposes only, would assist in keeping the Institution's records up to date by informing him of any change in their addresses or employment.

VOCATIONAL INSTRUCTION FOR THOSE TEMPORARILY SERVING IN HIS MAJESTY'S FORCES

The Institution, together with the Institutions of Civil and Mechanical Engineers, is co-operating with the Board of Education and the Advisory Council for Education in the Forces in the organization of courses in engineering subjects for those who wish to continue their studies while temporarily serving in His Majesty's Forces.

During the last war there was a break in the studies of a whole generation of engineers, with consequent loss to the profession; many on attempting to rejoin it had difficulty in resuming their studies and in passing their examinations, and were consequently handicapped. The Council regard it as of benefit that this experience should be avoided in the present war and they consider that the provision of courses of engineering study will not only provide useful mental occupation, especially during the winter months, should the conditions of the war allow a measure of study, but would also help those whose engineering training has been interrupted by the war to keep in touch with technical knowledge and perhaps, in some cases, to complete a portion of their engineering qualifications while still serving.

There are four methods by which the vocational instruction can be given, depending on the size and location of the unit to which the student is attached. Where a technical college is within convenient reach it is hoped that attendance at evening classes will be found possible. In large military centres where a sufficient number of students come forward, efforts will be made to arrange for the delivery of regular courses of lectures by qualified teachers. But there must remain a very large number

of cases, such as those of outlying and small stations, coast and anti-aircraft defences, in which courses of private study either by guided reading or by a modified form of correspondence course would be the only possible method.

It is in the framing of the last two methods that The Institution has been most concerned, and syllabuses of work suitable for guided reading or correspondence courses are now being prepared in the following subjects of a standard adapted to the Examination requirements of the Institutions:—

1. English	I.Mech.E. I.E.E.	Sec. A. Part II (a) Part I (1)
2. Fundamentals of Industrial Administration	I.Mech.E. I.E.E.	Sec. A. Part II (a) Part II. Group II (5)
3. Applied Mathematics (Engineering Science)	Inst.C.E. I.Mech.E. I.E.E.	Sec. A. I. Sec. A. Part I (a) Part I (2)
4. Physics and Chemistry (General Science)	I.Mech.E. I.E.E.	Sec. A. Part I (b) Part I (3)
5. Electrotechnics	Inst.C.E. I.Mech.E. I.E.E.	Sec. A. 3 Sec. B. (c.4) Part I (4)
6. Strength of Materials	Inst.C.E. I.Mech.E.	Sec. A. 2. Sec. B. (b)
7. Theory of Structures	Inst.C.E.	Sec. A. 4 (a)
8. Theory of Machines.	Inst.C.E. I.Mech.E.	Sec. A. 4 (b) Sec. B. (a)
9. Steam Engines	Inst.C.E. I.Mech.E.	Sec. B. Group 3 (3.a) Sec. B. (c.1)
10. Internal Combustion Engines	Inst.C.E. I.Mech.E.	Sec. B. Group 3 (3.b) Sec. B. (c.2)
11. Hydraulics	Inst.C.E. I.Mech.E.	Sec. B. Group 2 (1) Sec. B. (c.3)
12. Metallurgy	Inst.C.E. I.Mech.E.	Sec. B. Group 2 (3) Sec. B. (c.5)
13. Surveying	Inst.C.E.	Sec. B. Group 1 (1)
14. Geology and Mineralogy	Inst.C.E.	Sec. B. Group 3 (1)
15. Electricity Supply Electrical Installations	I.E.E.	Part II. Groups I and II
16. Electrical Communications		

Any student serving in His Majesty's Forces who is interested in the above arrangements should apply in the first instance to the Education Officer of the Unit to which he is attached, who will supply an enrolment form and details of the courses. Students of The Institution requiring further information or advice may communicate with the Secretary.

MEMBERS ON SERVICE WITH H.M. FORCES (SEVENTH LIST)*

(NOTE.—The Secretary will be glad to receive, for publication in subsequent lists, the names of other members of The Institution who are serving with His Majesty's Forces, together with particulars of their rank and the unit in which they are serving. A Roll of Honour, and lists of honours awarded, promotions, transfers, etc., are also being published from time to time.)

* See *Journal I.E.E.*, 85, p. 653; 86, pp. 99, 308 and 511; and 87, pp. 110 and 353.

Members

Name	Corps, etc.	Rank
Davis, B.	Royal Air Force (V.R.)	Pilot Officer
Jones, F.	Royal Signals	Major
Thouless, K. J.	Royal Signals	Major
White, B. G.	Royal Engineers	Major

Associate Members

Name	Corps, etc.	Rank
Adcock, W. H.	Royal Engineers	Captain
Agar, G. L.	2nd New Zealand Expeditionary Force	Major
Armitage, J. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Baldwin, N. V.	Royal Signals	Major
Barker, P. L.	Royal Army Ordnance Corps	Lieutenant
Bassan, M. L.	Royal Engineers	Sec. Lieut.
Bate, R.	Corps of Indian Engineers	Major
Bates, H. O.	Royal Army Ordnance Corps	Lieutenant
Bates, H. T.	Royal Naval Reserve	Lieutenant
Brook, R. V. C.	Royal Army Service Corps	Major
Cliffe, A. W. F.	Royal Engineers	Sec. Lieut.
Cooper, M. C.	Royal Signals	Major
Dewsnup, R. R.	Royal Engineers	Sec. Lieut.
Drake-Brockman, A. G.	Royal Engineers	Major
Dummelow, J.	Royal Engineers	Lieutenant
Dunford, L. G.	Royal Signals	Lieutenant
Fearon, P. V.	Royal Army Ordnance Corps	Lieutenant
Gibb, G.	Royal Naval Volunteer Reserve	Lieutenant
Hargreave, E.	Royal Army Ordnance Corps	Lieutenant
Hay, G. B.	Royal Engineers	Lieutenant
Jobling, H. B.	Transvaal Horse Artillery	Lieutenant
McCarthy, E. H.	Royal Engineers	Sec. Lieut.
McCormick, B.	Royal Engineers	Lieutenant
McInnes, R. E.	Royal Naval Volunteer Reserve	Sub-Lieut.
McLellan, D. H.	Royal Engineers	Captain
Micklam, G. V.	Royal Engineers	Major
Mildner, R. C.	Royal Air Force (V.R.)	Pilot Officer
Miles, P. P.	Royal Bombay Sappers and Miners	Lieutenant
Miller, R. C.	Royal Signals	Captain
Milne, W. H.	Royal Army Ordnance Corps	Lieutenant
Newman, J. B.	Royal Navy	Commander
Nield, H. B.	Royal Engineers	Sec. Lieut.
Page, A. R.	Royal Engineers	Sec. Lieut.
Parkinson, D.	Royal Engineers	Lieutenant
Percival, R.	Royal Engineers	Sec. Lieut.
Preedy, C.	Royal Engineers	Colonel
Procter, T. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Saunders, A. E.	Queen's Royal Regiment	Lieutenant
Simpson, R. M. O.	Royal Naval Volunteer Reserve	Sub-Lieut.
Taylor, C. M.	New Zealand Engineers	Lieutenant
Voelcker, J. W.	Royal Engineers	Sec. Lieut.
Watson, L. R. C.	Royal Signals	Major
Wilson, F. K.	Royal Signals	Major

Associates

Name	Corps, etc.	Rank
Barttelot, W. F. G.	Royal Engineers	Captain
Clayton, G. A.	Indian Army	Sec. Lieut.
Foster, W.	Royal Air Force (V.R.)	Pilot Officer
Newland, E. W. J.	Royal Engineers	Sec. Lieut.

Graduates

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Bakes, W.	Royal Air Force	A.C.2
Black, P.	Royal Army Ordnance Corps	Sec. Lieut.
Blackie, J.	Royal Engineers	Sapper
Bridcut, J. K.	Royal Naval Volunteer Reserve	Sub-Lieut.
Brown, H. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Chapman, R. C. G.	Royal Engineers	Major
Cooper, E. C.	Royal Army Ordnance Corps	Lieutenant
Fletcher, D.	Royal Engineers	Pioneer
Goering, P. H.	Royal Army Ordnance Corps	Lieutenant
Griffin R.	Royal Artillery	Sergeant
Hollingworth, S. I.	Royal Air Force (V.R.)	A.C.2
Houghton, E.	Royal Air Force (V.R.)	Flt.-Lieut.
Jamieson, I. A.	Royal Army Ordnance Corps	Sec. Lieut.
Keir, R. J.	Royal Air Force (V.R.)	Pilot Officer
King, C. J.	Royal Army Ordnance Corps	Lieutenant
Lieberman, L.	Royal Artillery	Gunner
Lonnon, P. W.	Royal Signals	Captain
McLachlan, W. S. H.	Royal Air Force (V.R.)	Pilot Officer
Maisey, H. R.	Royal Army Ordnance Corps	Lieutenant
Marsden, H. D. N.	Royal Engineers	Sec. Lieut.
Martin, T. D.	Royal Air Force (V.R.)	Pilot Officer
Masters, E. F. O.	Royal Air Force	Flt.-Lieut.
Mortimer, K.	Royal Engineers	Sec. Lieut.
Mulholland, E. B.	Royal Engineers	Sec. Lieut.
Nicholson, F. T.	Royal Army Ordnance Corps	Lieutenant
O'Hare, M. D.	Royal Armoured Corps	Trooper
Oswald, J. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Palmer, R. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Ray, D. H.	Royal Armoured Corps	Trooper
Reekie, G. R.	Royal Army Ordnance Corps	Lieutenant
Scott, P. J. M.	Royal Engineers	Sec. Lieut.
Shields, R. F.	Royal Army Ordnance Corps	Captain
Shipstone, B. A.	Royal Army Ordnance Corps	Lieutenant
Singh, G.	Royal Engineers	Sec. Lieut.
Smith, I. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Smith, J. N.	Royal Armoured Corps	Trooper
Stevens, P. F.	Royal Artillery	Sec. Lieut.
Taylor, D. P.	Royal Air Force (V.R.)	Pilot Officer
Venkataraman, M. K. R.	Royal Air Force	A.C.2
Walker, F.	Indian Army Ordnance Corps	Captain
Wertheim, J. M.	Royal Air Force	Pilot Officer
West, K.	Royal Signals	Signalman

Students

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Anderson, R.	Royal Engineers	Sapper
Andrews, K. R.	Royal Engineers	Lance-Corporal

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Applegate, J. R.	Royal Signals	Corporal
Armstrong, R. G.	Royal Signals	Sec. Lieut.
Baird, A. I. K.	Royal Army Ordnance Corps	Corporal
Barlow, J. F.	Royal Engineers	Sapper
Bowden, W. H. J. B.	Royal Artillery	Gunner
Brink, G. E. P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Brown, T. H.	Royal Naval Volunteer Reserve	Lieutenant
Chalmers, R.	Royal Artillery	Gunner
Davidson, A. M.	Royal Air Force	A.C.2
Donaldson, J.	A.A. Company (Australia)	Lieutenant
Draper, J. H. P.	Officer Cadet Training Unit	Cadet
Dunford, M. W.	Royal Artillery	Sec. Lieut.
Edwards, W. T.	Royal Navy	Lieutenant
Eshelby, R. A.	Royal Air Force	Leading Aircraftman
Flack, D.	Royal Engineers	Sapper
Frost, E. M.	Royal Artillery	Sec. Lieut.
Furnell, P. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Grant, E. L.	Royal Artillery	Gunner
Grant, W.	London Scottish	Private
Gray, R.	Royal Air Force	A.C.2
Griffin, J. G.	Royal Engineers	Sec. Lieut.
Hall, C. C.	Royal Navy	Engine-room Artificer
Hancox, N.	Royal Army Ordnance Corps	Staff Sergt.
Harper, S. D.	Royal Naval Volunteer Reserve	Lieutenant
Harston, J. M.	Royal Air Force (V.R.)	Aircraftman
Jewell, D. S.	Royal Air Force (V.R.)	Pilot Officer
Johnson, D. W.	Officer Cadet Training Unit	Cadet
Kennett, P.	Royal Signals	Signalman
King, E. S. F.	Royal Naval Volunteer Reserve	Lieutenant
Laight, A. H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Lang, R. M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Lewis, M.	Royal Air Force	Electrician, 1st Class
Lister, C.	Royal Air Force	A.C.2
Long, H. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mason, S. H.	Royal Armoured Corps	Trooper
Monk, H. W.	Royal Navy	Signalman
Moulson, R. W.	Royal Army Ordnance Corps	Lieutenant
Owens, J. G.	Royal Engineers	Sec. Lieut.
Paddon, C. E.	South African Air Force	Air Pupil
Patterson, L. S.	Royal Army Medical Corps	Lance-Corporal
Puttock, R. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Russell, W. D.	Royal Signals	Signalman
Sheffield, P. C.	Royal Navy (N.Z. Division)	Seaman
Smith, D. G. J.	Royal Engineers	Sec. Lieut.
Swanson, J. S. T.	Royal Naval Volunteer Reserve	Sub-Lieut.
Tinson, L. P.	Royal Air Force	Leading Aircraftman

OBITUARY NOTICES

FRANK ANSLOW was born in 1875 at Womborne near Wolverhampton, and was educated at Weston Grammar School, Bath. He served his engineering apprenticeship, first with the agricultural engineering firm of Henry Denton and Sons, and later as a pupil with the Electric Construction Co. at Wolverhampton. He then joined the firm of P. R. Jackson and Co., Salford Rolling Mills, as a draughtsman, and went from there to the Birmingham Electric Supply Co. as clerk of works and technical engineer in their Water Street station under the then chief engineer, Mr. J. C. Vaudrey. This was before the Birmingham Corporation took over the electric supply system. His next appointment was with Messrs. Johnson and Phillips at Charlton, where he was employed as chief draughtsman at the early age of 25. He left in September, 1900, to join the firm of Walter Dixon and Co., consulting engineers, Glasgow, of which firm he was sole partner at the time of his death. During his long association with this firm many large installations were undertaken, notably for the Ebbw Vale Steel, Iron and Coal Co., the Rothesay Dock of the Clyde Navigation Trustees, the British Plaster Board, and many other iron and steel and colliery companies, principally in Scotland and in the Midlands of England.

His wide range of engineering knowledge concerned the electrical and mechanical equipment of ironworks, steelworks, plaster works, collieries and general industrial works, comprising rolling-mill equipment (in which he specialized for over 25 years), colliery winding-plants, electric furnaces, etc. He also advised local authorities and county councils in Scotland on rural electrification and matters arising out of the McGowan Report.

He was elected an Associate Member of The Institution in 1903 and a Member in 1906, and served on the Committee of the Scottish Centre in 1918-21. He was also a member of long standing of many other technical Institutions, including the Association of Mining Electrical Engineers, of which he was one of the founders and a Past President. For the technical journal of that society he did invaluable work, being convener of the Publications Committee since its inception. At various times he also contributed papers on current engineering matters to several technical Institutions.

Firm in character, shrewd in judgment, and of an amiable and equable disposition, he trained many engineers now holding responsible posts in the engineering world, who continued to regard him as friend and adviser.

"R. B. M.

RALPH MELVILLE ARCHER died at Farnborough, Hants, on the 14th April, 1940, at the age of 66. Born at Southampton on the 10th July, 1873, he was educated at Taunton's School and at Hartley College, Southampton. Entering the Royal College of Science in 1891 with a National Scholarship, he obtained the diploma

of the College and later the B.Sc. degree of the University of London with honours in physics. After 2½ years as demonstrator in physics at the Royal College of Science, he was appointed lecturer at Battersea Polytechnic. From 1900 to 1918 he was head of the electrical engineering department and lecturer in physics at Derby Technical College. In all these and his later educational appointments he revealed those qualities of enthusiasm for his subject, originality in his methods, and sympathy with the needs and difficulties of students, which endeared him to all who came under his charge. It would be difficult to overestimate the ultimate influence and value of his genius for devising methods and apparatus of maximum simplicity combined with scientific integrity and technical quality, whether for purposes of demonstration, use by students, or use in pure and applied research.

Leaving Derby in 1918, on appointment to the Instrument Section of the Air Ministry, he embarked on a long series of researches relating to liquid oxygen apparatus, compass interference, fog-landing and other subjects, partly in London and partly at the Royal Aircraft Establishment, Farnborough. He was responsible for a large part of the 1923 Report of the Oxygen Committee of the Department of Scientific and Industrial Research, and other results of his activities during this phase of his career, terminated in 1933 under the age limit, are embodied in the successful solution of many intricate problems demanding a rare combination of scientific knowledge, ingenuity, craftsmanship and patience.

From 1933 until the onset of his last illness he was evening lecturer in electrical engineering at the Farnborough Technical School (1933-39), Borough Polytechnic (1933-38), and Northampton Polytechnic (1938-39). His educational work during this period, restricted only by operation of the age limit, was no less valuable than that of his earlier life. At the same time, all his available leisure was devoted to continuance of research in his private laboratory, which in itself was a remarkable demonstration of his industry, versatility and devotion to science. Almost to the last his mind was occupied productively on a programme of work from which much of high value might well have come, had his physical powers endured.

In all things, his treasure and his heart were in the temple of truth on the altar of service. He leaves an abiding memory of a sterling and kindly character, passionately opposed to injustice and pretence, infinitely sympathetic and helpful in the difficulties of others. His scientific and technical books and papers, published during a period of more than 30 years, reflect his scrupulous attention to detail and the high standards to which he adhered. Mountaineering, cave exploration and devotion to music were other facets of a life and character that knew nothing small, nothing mean.

He was elected an Associate of The Institution in 1901 and a Member in 1906.

R. E. N.

OSCAR HOWARD BALDWIN, who was elected a Member of The Institution in 1907, died on the 14th February, 1940, at the age of 75, after a long illness which he bore with unexampled fortitude and courage. Born in the United States, he remained an American citizen, although resident in England during practically the last 50 years of his life.

He was one of the old Westinghouse pioneers in this country and his early recollections of the electric supply industry were published in vol. 60 of the *Journal* in connection with the I.E.E. Commemoration Meetings held in 1922.

After some time with Westinghouse, Church, Kerr and Co., and the Westinghouse Electric and Manufacturing Co. in the United States, he came to London in 1889 for the latter company. He developed the sale of the Shallenberger meter, which, in its time, was one of the best alternating-current meters on the market, and he supervised the erection of Westinghouse plant at the Sardinia Street station of the Metropolitan Electric Supply Co. This was a belt-driven plant, with vertical enclosed engines on the ground floor and single-phase generators on an upper floor.

After a short visit to the States he returned to England in charge of the Westinghouse Co.'s foreign sales department, and later he became managing director of the Westinghouse Electric Co. of London. From 1900 to 1902 he was managing director of J. G. White and Co., and was associated with the late Mr. A. N. Connett in the electrification of the first section of the L.C.C. tramways, on the conduit system. During this period the writer was thrown into close contact with him, and cannot speak too highly of the sound engineering shown and the honest work done by Baldwin and Connett on behalf of their firm.

In 1902 he returned to the British Westinghouse Electric and Manufacturing Co. (later Metropolitan-Vickers) as district manager and remained with them until his retirement in 1928. From 1928 to 1933 he was a director of the Taylor Stoker Co., and in that position showed the same keenness and honesty in his work which had for long been his characteristics.

The writer's business relations with Oscar Baldwin over a period of more than 40 years developed into a personal friendship which continued until his death. During the latter years of his life he resided at Salcombe, Devon, within sight of the sea which he loved. He leaves a widow and two daughters to mourn his loss.

J. H. R.

EDWARD BARRS was born on the 17th December, 1881, and was educated at Marlborough College and the Crystal Palace School of Engineering. He then entered the service of Messrs. Bramwell and Harris, consulting engineers, Westminster, as a pupil and subsequently was employed by them as a junior engineer. In June, 1903, he was appointed assistant engineer on the staff of the South Wales Electric Power Distribution Co. Two years later he returned to Messrs. Bramwell and Harris and assisted them in the preparation of specifications and the supervision of the erection of plant. For a short time he was on the staff of Dr. C. H. Merz and was then appointed

consumers' engineer by the Cleveland and Durham Electric Power Co. and the Northern Counties Electric Power Co. In May, 1909, he resigned and set up as a consulting engineer with Mr. Tennant at Newcastle-on-Tyne, the firm being known as Messrs. Tennant and Barrs. The firm acted jointly with Mr. J. F. C. Snell (later Sir John Snell) as consulting engineers to West Hartlepool Corporation and also acted in an advisory capacity to various colliery companies and waste-heat undertakings. When the partnership was dissolved Mr. Barrs joined Mr. C. A. Ablett and they carried on a consulting engineering practice not only at Newcastle-on-Tyne but also at London and Cardiff. Subsequently Mr. Barrs carried on his consulting practice independently at Gray's Inn, London, specializing in power plant equipment and factory layout. Owing to continued ill-health he had eventually to retire from active business and he died on the 1st July, 1940. He joined The Institution as an Associate Member in 1910 and was elected a Member in 1913.

ROBERT BLACKMORE died at St. Annes-on-Sea on the 4th December, 1939, at the age of 66. Born in London, where he served his apprenticeship with Mr. Clough and Messrs. Davy and Co. and attended evening classes at the Finsbury Technical College, he joined the St. James's and Pall Mall Electric Light Co. in 1896 as charge engineer. In August, 1898, he was appointed outside superintendent over distribution for the National Electric Supply Co., Preston, and later was made assistant to the chief engineer, relinquishing the post in May, 1900, to become city electrical engineer at Wakefield. Two years later he was engaged as assistant to A. H. Gibbins, consulting engineer to the Stalybridge, Hyde, Mossley and Dukinfield Transport and Electricity Board, of which he became engineer-in-chief in 1905. He retained this position until his appointment as the Central Electricity Board's district manager for North-West England and North Wales. Failing health caused him to tender his resignation and he was due to retire at the end of 1939, but death intervened.

During his period at Stalybridge, he was a pioneer of cheap electricity supplies to textile factories, and was consulting engineer to a large number of cotton, woollen and lace mills in different parts of the country, also to many electric supply undertakings in Lancashire and Yorkshire. He took an active interest in the District Joint Industrial Council for the Electricity Supply Industry in North-West England and was chairman of the Executive Committee from 1922 to 1929. He was also a founder member of the District Joint Board for the same area and retained his membership from 1919 until his C.E.B. appointment.

He was possessed of a strong personality, which found expression in his work on the Whitley Council and Joint Board, as well as in his direction of the Grid development in the North-West England area. Unswerving in purpose once he had decided on a policy, he listened carefully to reasoned criticism. A strict disciplinarian, he was invariably fair in dealings with his staff. In all his professional activities he subordinated everything

to the advancement of the undertaking or firm he was serving.

He was elected an Associate Member of The Institution in 1908, and a Member in 1930.

H. C. L.

C. T. S. A.

HENRY BURKINSHAW was born on the 26th September, 1881, and died on the 22nd November, 1939. Educated at King Edward VI School, Norwich, and at Knutsford Grammar School, he studied electrical engineering under Prof. Ewing at Cambridge from 1897 to 1898. From 1898 to 1903 he was a pupil at the Newcastle works of Messrs. C. A. Parsons and Co., continuing his studies at evening classes at the Durham College of Science and at Rutherford College, Newcastle. In 1902 he was appointed an assistant turbine designer with the British Thomson-Houston Co. In 1905 he became resident engineer at Radcliffe for the Lancashire Power Co., acting in the capacity of power-station superintendent and being responsible for all engineering work carried out on consumers' premises in connection with the conversion of plant for operation from the public supply. Resigning this position in 1907, he was engaged for some years on power and mining engineering contracts in England and India for Siemens Brothers Dynamo Works, for whom he served as branch manager in Calcutta and subsequently as general manager for India.

He left Messrs. Siemens in 1916 to join the Military Works Branch, Army Headquarters, Simla, as a civilian engineer, and the following year became controller of electrical and mechanical engineering to the Indian Munitions Board. Later, in January, 1919, he joined the staffs of Messrs. Bird and Co. and Messrs. Heilgers and Co. of Calcutta, which firms he left to set up as a consulting engineer on his own account. This business was most successful, and it was only failing eyesight, due to working for long hours at night, that caused him to relinquish it. He then joined Messrs. Marshall and Sons (India) as a director, and remained with this firm about two years. He was then offered, and accepted, the position of agent and chief engineer of the Madras Electric Supply Corporation, later becoming a director, and he remained with the Corporation until his death.

He was elected an Associate Member of The Institution in 1909 and a Member in 1921, and he played a prominent part in the activities of The Institution in India, serving on the Committee of the Calcutta Local Centre (1915) and as Acting Local Hon. Secretary and Treasurer for India (1922). He was Chairman of the Membership Advisory Committee for India from its inception until the setting-up of the Local Committees, and shortly before his death was appointed Vice-Chairman of the Madras Local Committee.

He was closely connected with the formation of The Institute of Engineers (India), holding the office of President during one year. He was well known to electrical engineers all over India, particularly excelled as an after-dinner speaker, and his knowledge of electrical matters in India was large and varied. His death is a great loss to the profession generally, and he will

be very greatly missed at all gatherings of electrical engineers in India, where most of his life was spent.

He was a widower for many years and leaves a son, who has joined the medical profession. C. C. T. E.

COLONEL JOSEPH CHARLES CHAMBERS, C.B., was born at Stockton-on-Tees on the 31st January, 1857, and was the eldest son of the late John Charles Chambers, one time superintending engineer of the North-Eastern District of the Post Office Engineering Department. He received his early education at a private school and followed his father into the Engineering Department of the Post Office in December, 1870, where he gained experience in telegraph construction. In 1880 the United Telephone Co. acquired the telephone system already established in Leeds and neighbouring towns by Messrs. Blakey and Emmott of Halifax, and in June of that year he was engaged by that company and was appointed manager at Leeds on the 29th July, 1880. The United Telephone Co.'s interest in Leeds and the surrounding neighbourhood passed successively into the hands of the Yorkshire Telephone Co., the Provincial Telephone Co. and, in 1881, the National Telephone Co. He filled in rapid succession the posts of local manager at Leeds, district manager at Hull, and district manager for Yorkshire, and in 1893 when the telephone service had developed considerably a new organization was established, control was decentralized and he was appointed provincial superintendent of the Northern Province, with headquarters at Leeds. In this capacity he remained until the 31st December, 1911, when he relinquished his connection with the telephone business owing to its acquisition by the Post Office.

Col. Chambers had a long military experience. For 14 years he served in the 1st Durham Light Infantry. He then joined the Leeds Rifles in 1887 as a lieutenant and after 4 years became captain. In 1898 he was appointed honorary major and instructor of musketry to the battalion. He served as adjutant to his battalion during the South African War and took a staff appointment at York. In 1908 when the Territorial Force was created he raised the West Riding Divisional Army Service Corps, and on the outbreak of war in 1914 he took the Corps to France. He was mentioned in despatches and in January, 1916, received the C.B. On his return to this country a few months later he was placed on the reserve.

Church institutions and medical charity organizations in Leeds owe much to his organizing ability. At one time he was one of the Wardens of Leeds Parish Church and later occupied a similar position at All Hallows. He was hon. secretary of Leeds Church Institute since 1909 and was closely associated with the activities of the Leeds Church Extension Society. He served on the management committees of Leeds Public Dispensary and Cookridge Convalescent Hospital, relinquishing the chairmanship of the latter institution only shortly before his death, which occurred on the 6th February, 1940.

He was elected an Associate of The Institution in 1884 and a Member in 1886.

F. G. C. B.

FRANCIS WILLIAM CLEMENTS died at Melbourne on the 12th December, 1939, at the age of 75. Since

December, 1937, he had lived in retirement, having on that date relinquished the chairmanship of the State Electricity Commission of Victoria, a position which he had held for years. For several years previous to this he had been one of the members of the Commission.

A pioneer in electric supply development, he was closely associated with the Brush Electrical Engineering Co. in England, and the late W. M. Mordey, in designing and establishing some of the earliest electric lighting systems in Europe; and in connection therewith he made prolonged stays in Austria, Hungary, Finland and other countries. He became later associated with the County of London Electric Supply Co. in its several pioneer undertakings, and for a time was in charge of the St. Luke's power station.

In 1899 he went to Australia under an arrangement with the Brush Company to complete negotiations for the acquisition of several electrical undertakings in Victoria and South Australia, and to investigate proposals in other States. On the completion of these negotiations the Electric Lighting and Traction Co. of Australia was formed, of which he became local managing director and chief engineer. In 1908 the company changed its name to the Melbourne Electric Supply Co., and, later, with the transfer of the financial and administrative control to Australia, Mr. Clements became its managing director, an appointment which was terminated only when he accepted a Commissionership under the State.

The remarkable success of the company, in making available an economic and universal supply throughout the widely scattered areas of the franchise, served as a tribute to his technical and commercial abilities and the far-seeing imaginative faculty which enabled him to visualize possibilities to a greater degree than most of his contemporaries.

In 1917 he accepted a seat on a board to advise the Government as to the possibility of utilizing the great brown coal resources within the State for the production of power. The Report which ensued was the forerunner of the State system of power production, the extent of which to-day makes it one of the outstanding undertakings in the world.

In Australia, Mr. Clements was looked upon as the "doyen" of the electricity supply industry. For his distinguished services in the realm of engineering science he was awarded the Kernot Memorial Medal and the Peter Nicol Russell Memorial Medal, the latter being the highest honour which his professional brethren in the Institution of Engineers, Australia, could confer upon him.

Notwithstanding a remarkable record of engineering achievement, he will be best remembered by a large circle of associates for his delightful personal qualities, of which not the least was an unassuming modesty. Widely read and well informed, there were but few subjects in science and art to which he could not make some worthy contribution. Relaxation was sought in photography, in which he was an adept, and microscopy. Retirement afforded him the opportunity to exercise his love for music, of which he was a connoisseur, and his intimate knowledge of French and German afforded him a wide scope of both technical and general reading.

He joined The Institution as a Member in 1896.

H. R. H.

SAMUEL WILLIAM CORNS, who died on the 22nd February, 1940, was born in December, 1878, at Wolverhampton, and was educated at Douro House School, Wolverhampton, Wolverhampton Technical School, and the Finsbury Technical College. He served an apprenticeship with Messrs. Davies Brothers and Co., constructional engineers, at Wolverhampton, and later as improver and draughtsman with the Electric Construction Co. In 1903 he joined the British Thomson-Houston Co. at Rugby as a draughtsman, but left in 1904 to take up a similar position in the carriage and wagon department of the Metropolitan Railway. In 1906 he accepted the appointment of chief draughtsman to the chief electrical and mechanical engineer, and was appointed assistant engineer in 1913. In 1921 he became assistant mechanical and electrical engineer, and in 1923 when, owing to expansion, the electrical and mechanical Departments became separated, he was appointed assistant electrical engineer. In January, 1934, following the formation of the London Passenger Transport Board, he was appointed assistant electrical engineer (Metropolitan Section), and in 1937 assistant electrical engineer (generation) of the Neasden Section, which office he retained until his death.

He thus acquired a very intimate knowledge of all sides of electric railway working, and took a particular interest in the special types of locomotive which were developed for use on the Metropolitan Railway, the characteristic appearance of which must be well known to all travellers thereon. In later years he suffered very poor health, but the serious operations which he had to undergo in no way affected his characteristic cheerfulness and fortitude, and his ultimate death came as a sudden blow to his many friends and colleagues.

He was elected a Member of The Institution in 1923.

A. L. L.

COLONEL ROOKES EVELYN BELL CROMPTON, C.B., F.R.S., died on the 15th February, 1940, in his 95th year after a wonderful innings full of adventure and achievements. He was a great pioneer and was always in the van of progress, interested in new ideas with a mind which never grew old.

Among the disadvantages of living so long is the inevitable loss of practically all one's contemporaries, but his youthful outlook on life enabled him to make new friends, and a wonderfully varied assortment of people found their way up in his antiquated lift to his laboratory and study at the top of his house in Kensington Court. Although he had moved in exalted circles both here and abroad he was as genuinely pleased to see any of his old workmen as he was to see the highest in the land. He would be interested in the welfare and doings of one and all, and no one ever saw their friends through rosier spectacles. Indeed, his introductions were sometimes quite embarrassing and certainly took a good deal of living up to. He was completely uninterested in malicious gossip and took everyone just as he found them. He had a marvellous sense of humour and loved jokes of every kind.

One of the present writer's earliest recollections of Colonel Crompton was going with him at the beginning of 1903 in his steam car down to Berry's transformer

works at Hayes, Middlesex. We arrived in due course without incident and spent some time there, but when we were ready to leave and got into the car it refused to move, the fact being that the boiler had burst, as he had omitted to turn off the steam on arrival. How we got back to town is now forgotten, but at any rate as the Colonel was still very fond of his long-crank bicycle he used that means of conveyance while the car was out of commission.

He was an enthusiastic advocate of electrical standardization, which at that time was just getting under way, and he was chairman of the Engineering Standards Sub-Committee dealing with motors and generators. This work was sufficiently advanced in 1904 to enable him to present a paper to the St. Louis Electrical Congress which was presided over by Dr. Elihu Thomson. This was the beginning of a long, intimate and warm friendship between the two men.

The paper before that Congress resulted in the well-known resolution being passed by the Government Chamber of Delegates which initiated the movement leading to the formation of the International Electrotechnical Commission (known as the I.E.C.) in London in 1906. For many years Colonel Crompton was the enthusiastic Honorary Secretary and moving spirit in the international meetings which were held at regular intervals in different parts of the world. His whole training and general outlook on life made him most successful in working with men of many different nations. Moreover, his keen sense of humour and his innate good manners enabled him to enjoy even the long and somewhat tedious speechifying so inseparable from such occasions. He was himself a fluent and apt speaker and could be trusted almost up to the end of his life to make a good impromptu speech. When difficulties arose in the I.E.C., as they are bound to do in any progressive movement, he was a tower of strength and an able ambassador of peace. As time went on and it was no longer possible for him to take such an active part in the international work he was elected Honorary President and he still continued, whenever possible, to attend the large meetings and was always received with an affection which bordered on reverence, for he was looked upon, as indeed he was, as the father of the I.E.C.

The many accounts which have appeared in the technical Press of his pioneering work in the development of the electrical manufacturing and electricity supply industries render it unnecessary here to set out those details; moreover, they can be read in his published "Reminiscences," which also contains particulars of his career as a soldier, road engineer, motorist, etc. For the *Journal* it must suffice to refer merely to his association with The Institution.

Colonel Crompton joined The Institution as an Associate in 1880 and was elected a Member in the following year. He served as an Ordinary Member of Council from 1884 to 1889 and as a Vice-President from 1890 to 1894. In 1895 he was elected President, and again on the 9th January, 1908, for the remainder of that session on the death of Lord Kelvin during the latter's presidency. In 1923 he was elected an Honorary Member, and in 1926 he was awarded the Faraday Medal. From the earliest days of his connection with

The Institution he took an active part in its proceedings, and the *Journal* contains at least nine papers which he read at meetings, and innumerable contributions to discussions. In these in the eighties and nineties when the relative merits of direct current and alternating current for a public electricity supply were so often debated, he was always a strong advocate of the d.c. system.

He took a prominent part in raising by the help of The Institution the corps of Electrical Engineer R.E. Volunteers, who offered their services to the Government in connection with the South African War. He himself took command of the corps and went with it to South Africa in 1899-1900. On their return to this country he read a paper before The Institution describing the war services of the corps.

One of his last appearances at The Institution was on the occasion of the presentation of his portrait at the Ordinary Meeting held on the 7th November, 1935, when he made a short speech which will be found in vol. 78 of the *Journal*.

Though most of his life was spent in cities working with machines or sitting on committees, he had an understanding love of the countryside and was always to be found on the side of the angels when matters dealing with its care and preservation were concerned. Though a devoted Londoner he, nevertheless, much enjoyed his long summer visits to his Yorkshire home, where the writer last saw this really remarkable old man some months before his end still keenly interested in all the affairs of the great world outside.

C. LE M.

ALEXANDER DAVIDSON, who died on the 3rd January, 1940, at Benchams, near Sidmouth, Devon, was born at Mauchline, Ayrshire, on the 7th June, 1870, and at an early age started his life-long career in electrical communication in the telegraph side of the Post Office at Mauchline, Greenock and Glasgow, beginning in the capacity of telegraphist. At Glasgow he attended the Glasgow and West of Scotland Technical College (now the Glasgow Royal Technical College), where Andrew Jamieson was the professor of electrical engineering.

In 1892 he became assistant electrician in the Anglo American Telegraph Co.'s cable ship "Minia," in the Atlantic, and was subsequently chief electrician in the c.s. "Mackay Bennett," of the Commercial Cable Co., and in the c.s. "Relay" and the c.s. "Guardian" of the Central and South American Telegraph Co.

After his extensive sea-going experience, he became, in June, 1914, acting superintendent, Southern Division at Lima, Peru, and in February, 1916, general superintendent on the Pacific Coast. In November, 1917, he was appointed general manager at New York, and in July, 1918, vice-president in charge of operations, all in the service of what is now All America Cables and Radio Inc. In 1923 he returned to England as vice-president of All America Cables, and in 1936 was appointed European telegraph communications representative of the International Telephone and Telegraph Corporation, which position he held to the end of his life. He was also a director of Messrs. Creed and Co. and of the International Marine Radio Co.

He attended many International Conferences, and lesser meetings attendant on them, at all of which he was a well-known and respected representative. As a committee member, very often as chairman, of the International Telegraph Companies' Association, he did valuable work, and his sage counsel, imperturbability, constant courtesy and happy knack of composing differences were greatly valued. His cheery disposition, vision and broadmindedness are affectionately remembered by a large circle of friends and by all with whom he came in contact. In 1901 he married Mary, elder daughter of James Bremner, of Lima and Kirkcaldy, by whom, and by one son and one daughter, he is survived.

He was elected an Associate of The Institution in 1897 and a full Member in 1909. F. G.

HUGH DENEHY, assistant consulting electrical engineer of the Central Mining and Investment Corporation, died at Johannesburg on the 21st February, 1940. Born in Okla, India, in 1883, he went to South Africa in 1907 as electrical engineer under contract with the Natal Government Railways, and was afterwards associated in the capacity of electrical engineer or resident engineer with various mines of the Central Mining—Rand Mines Group, among these being City Deep, Crown Mines, Nourse Mines, New Modderfontein, Modderfontein "B." and Transvaal Gold Mining Estates. He was also, for a time, chief engineer of Trinidad Leaseholds.

He was an able and experienced electrical engineer and a keen photographer, and he possessed a charming disposition. A man of unfailing urbanity, he was a staunch friend and was exceedingly popular with all with whom he came in contact. Of a generous nature, he was ever ready to help those in less fortunate circumstances than himself. He is survived by his wife, two sons and a daughter.

He was elected an Associate Member of The Institution in 1910 and a Member in 1923. W. E.-D.

HERBERT JULYAN DONKIN, M.B.E., was descended from a long line of eminent engineers. He was educated at St. Paul's School, Kensington, and at the University of London. In 1908, having completed a two years' apprenticeship with the Simms Manufacturing Co. of Kilburn, he joined Messrs. Humphreys and Glasgow, of Westminster, and was engaged in the drawing office and on erection work of water-gas plant. From 1910 to 1912 he was engineer in charge of contracts carried out by Messrs. Woodall and Duckham of Westminster, in connection with the installation of vertical retorts for the carbonization of coal. He then went to Ceylon as mechanical engineer to the Public Works Department of Colombo Municipality, but resigned the appointment in 1915 and received a commission in the Royal Engineers, with whom he served for three years in Mesopotamia, and attained the rank of lieutenant-colonel. He was later gazetted major, a rank he held until his death. In 1918-19 he was assistant director of works at Kut-el-Amara. Subsequently he was transferred to the North-West Frontier Force, becoming assistant director of works at Khyber Pass. Here he carried out important work in installing a series of

reservoirs and pumping stations to provide a water supply to the Khyber Pass; this removed one of the principal difficulties of military operations in that region. During 1920-21 he held an appointment with Messrs. Humphreys and Glasgow, but returned to India in the latter year upon his appointment as superintending engineer (electrical and mechanical) of the Public Works Department, Delhi. He was responsible for all mechanical and electrical work carried out in the Province and, *inter alia*, constructed and equipped three pumping stations for New Delhi. After his retirement from this position in 1934 he accepted the position of general manager of the Delhi Electric Supply and Traction Co., which he occupied until his death on the 20th July, 1939, in his 53rd year. He was elected an Associate Member of The Institution in 1928 and a Member in 1936.

S. B. D.

FREDERICK HENRY EDWARDS, borough electrical engineer of Dartford, died on the 16th April, 1940, at the age of 62. He was educated at Kilburn Grammar School and at the Regent Street Polytechnic, and commenced his career with the Hampstead Electric Supply Co. in 1898 as shift engineer. He subsequently held similar appointments with the Stepney Borough Council and the London United Tramways.

In 1906 he became deputy electrical engineer to the Woolwich Borough Council, in 1909 deputy electrical engineer and tramways manager at Erith, and, in 1912, deputy electrical engineer to the Cornwall Power Co. at its Hayle generating station. In October, 1919, he was appointed borough electrical engineer and manager of the Dartford Corporation Electricity Department, a position which he held for 21 years until his death. During the last two years of his life he had been in indifferent health, yet to the last he remained concerned for all, unconcerned for himself. He leaves a widow and two sons. He was elected an Associate Member of The Institution in 1906 and a Member in 1922. R. D.

WILLIAM BEEDIE ESSON, who died on the 9th May, 1940, at the age of 82, was one of the few surviving pioneers of the epoch during which the heavy electrical industry, as distinguished from signalling, was developed from a dwarf into a giant.

Born in 1858, he received his early education in his native Aberdeen, and later achieved distinction at the City and Guilds Institute. After experience as a draughtsman with the Thames Ironworks and Shipbuilding Co., he joined Messrs. Paterson and Cooper at the age of 25, and remained with them for 9 years. In 1892 he became manager of the Gulcher Electric Light and Power Co., and carried out many electricity supply schemes, including that for Wellington, New Zealand.

In 1894 began his fruitful connection with Messrs. Johnson and Phillips, where he managed the electric light and power transmission departments. In this capacity he designed long-distance transmissions for various gold mines in Burma and Africa, and many power plants for installation at home and abroad. He was keenly interested in the theory and design of electrical machines, both direct-current and alternating-

current. In his young days the construction of dynamos, motors and transformers was largely a matter of rule of thumb. Theories were incomplete and often fantastic; there were more unknown than known factors. Esson was one of the ingenious and persevering band who gradually evolved order from chaos, and who persuaded practice and theory to run in parallel. As a consequence there was a startling advance in efficiencies, and a corresponding cut in sizes and prime costs for a given output.

Many were the ingenious improvements and developments which stand to Esson's credit. Some of these form the subject of papers read before The Institution, others are recorded in the technical journals of the period. As far back as 1885 he had made a fundamental contribution to transformer design by advising Messrs. Gaulard and Gibbs to connect the cores of two secondary generators at the top and bottom, thus completing the magnetic circuit. In 1897 the Silver Medal of the Royal Society of Arts was awarded to him for his paper on "Transmission of Power to Long Distances by Alternating Currents."

In 1904 he retired from active work with Messrs. Johnson and Phillips and thereafter practised as a consulting engineer, and for 36 years he was a director of the Chiswick Electricity Supply Corporation. During his career he did useful work on many committees, particularly the Engineering Standards Committees.

He joined The Institution as an Associate in 1884 and was elected a Member in 1886, and in 1894-96 he served on the Council. In 1890 he was awarded the Institution Premium for his paper entitled "Some Points in Dynamo and Motor Design." In the following year he read a paper on "The Design of Multipolar Dynamos," and in 1903 one entitled "Recent Electrical Design." At the Commemoration Meetings in 1922 he contributed a paper entitled "Some Early Recollections of Dynamo-Electric Machinery."

Personally he was kind-hearted and genial, and entered with zest into the social life of the electrical community. Those of his old friends who remain will always picture him as smiling. They will also recall the charming little Dresden-china figure that was Mrs. Esson. She was born in Rome, a descendant of the Giustiniani family, and her father had fought with Garibaldi.

R. W. H.

FREDERICK J. EVANS, who was elected a Member of The Institution in 1904, died on the 17th February, 1940, aged 78. From 1885 to 1889 he was employed as an assistant by Messrs. Elwell, Parken, at Wolverhampton, and was engaged on armature winding and testing. He then spent a year in erecting plant for Messrs. Crompton and Co. at Barry Docks. In 1890 he was appointed electrical engineer to the Barry Railway Co., and was responsible for the electrical plant supplying electric light and power for the railway and docks. He retired from the railway in 1923 after 33 years' service.

J. B. G. L.

RANDELL HOWARD FLETCHER, B.A., who was born in 1869 and died on the 19th December, 1939, at the age of 70, was educated at Cambridge University,

being an undergraduate at Emmanuel College where for a time he was President of "Lions."

He was very directly concerned with the erection and equipment of the Cardiff Corporation's original generating station at Eldon Road, after which—from 1899 to 1906—he was a member of the firm of Messrs. Herbert Lewis and Fletcher, electrical engineers and contractors, who carried out many of the big installations of electric lighting and power in the city and surrounding valleys. In 1906 the firm gave up their business as such and entered into practice as consulting engineers, and were responsible for the preparation of a number of important schemes on behalf of local and other authorities in the North and South Wales districts.

In 1915 the partnership was dissolved by mutual consent when the late Sir Herbert Lewis, Commissioner of the Order of St. John for Walesre, tired, Mr. Fletcher taking over the whole of the practice until his retirement in 1929. During the period of 14 years he was actively connected with electricity undertakings as engineer and adviser, and was one of the pioneers of overhead distribution in the South Wales district.

He was elected an Associate of The Institution in 1891, an Associate Member in 1899, and a Member in 1903, and was Chairman of the Western Centre in 1917.

Mr. Fletcher was a quiet, unobtrusive and most likeable man and was held in very high regard by all those who had the privilege of his friendship. He was strongly conservative in practice and a very able business man. His imagination was in the highest sense concrete, grasping the actual reality and not only the relation of things. He spread his knowledge or experience gained in theory or in practice to work of improving human progress and efficiency in the younger profession, and he constantly gave voluntary help and assistance to inventors of electrical apparatus for the improvement of the industry.

A. E.

HUGH WELBOURN GREGORY was born at Hampstead, London, in 1886. From the Philological School, now St. Marylebone Grammar School, he proceeded to the City and Guilds College at Finsbury where he studied electrical engineering under the late Prof. Silvanus Thompson. Having been awarded the College Diploma he obtained a position as a junior at the Salusbury Road substation of the Willesden Council. This started his life interest in the supply industry. After 2 years he proceeded to the Coventry Corporation, but within a year he joined the North Metropolitan Electric Power Supply Co. as first assistant engineer at High Barnet. After a period there he was appointed, in 1910, to West Ham Corporation as power representative, in which position he was responsible for the electrification of many large factories in the Silvertown and Canning Town districts.

During this period he took a keen interest in the London Students' Section of The Institution and served as a member of the committee. He contributed papers, and that on "The Motor Convertor," read in 1908, was awarded a Students' Premium and was published in the *Journal* (vol. 41, p. 803). For 2 years from 1912 he was superintendent of the Dolgarrog hydro-electric station of the Aluminium Corporation. He then

returned to the North Metropolitan Co. as resident engineer for the new Wembley district, during which time he was responsible for the electrical installation of the Empire Exhibition at Wembley. He later became superintendent of the western area of the Northmet Power Co. until he was placed in charge of the northern area at Hatfield in 1937 and in 1938 of the north-western area. He had hopes about 1911 of being appointed to the distribution side of a new power company in Canada, designing and erecting substations, but the appointment did not materialize.

He was a recognized expert on public lighting and at the time of his death was vice-president of the Association of Public Lighting Engineers. From 1933 he represented The Institution on the British National Committee of the International Illumination Commission and the Illumination Industry Committee of the British Standards Institution. He also represented the Association of Electric Power Companies on the B.S.I. Street Lighting Committee and he was a member of the E.D.A. Committee on Street Lighting.

He was untiring in his attention to the trusts imposed on him, and his great sense of duty no doubt caused the breakdown from which he never really recovered. He was held in high esteem by all who knew him.

He was elected a Student of The Institution in 1904, an Associate Member in 1912 and a Member in 1930.

E. W. M.

SIR ROBERT ABBOTT HADFIELD, Bart., F.R.S., died on the 30th September, 1940. Born in Sheffield in 1859, he was educated at the Sheffield Collegiate School and studied engineering privately in the laboratory which his father, the owner of a steelworks at Attercliffe, had erected for his use. As a young man he was responsible for extending greatly his father's works, but he also found time to carry on the researches which led him in 1882 to the production of the first specimen of manganese steel. He later put this material to many uses in engineering where great resistance to wear is required, e.g. in the manufacture of tracks for tramways and railways. In 1889 he produced low-hysteresis steel, an alloy of silicon and iron, and this has proved invaluable as a means of improving the efficiency of transformers. When his father's firm was turned into a limited company he became at a comparatively early age its chairman and managing director. During the war of 1914-18 the company devoted itself to the large-scale production of armaments. In later life Sir Robert carried out an examination of the specimens of various steel alloys which had been prepared by Faraday about a century previously and had been preserved by the Royal Institution.

In recognition of his valuable contributions to the science of metallurgy, honours were showered upon him by universities and learned societies throughout the world. He was made an F.R.S. in 1909, was knighted in 1908 and received a baronetcy in 1917. In 1921 the four main engineering societies of the United States sent a deputation to England to present to him in person the John Fritz Medal, the highest honour American engineers can bestow.

He was elected a Member of The Institution in 1904,

and served on the Council for the period 1918-20. Two of his papers on the electrical and magnetic properties of iron alloys were read before The Institution, and for the second, in 1911, he was awarded the Institution Premium.

LEO ARTHUR HARDS died on the 1st September, 1940, at the age of 71. He was educated at Rugby School, attended evening classes at the Finsbury Technical College, and obtained his practical training with Messrs. Shirlaw and Co., engine builders and toolmakers, Birmingham, and later with Messrs. Woodhouse and Rawson, electrical engineers, Hammersmith. In 1889 he joined Messrs. Edmundsons as a junior engineer, and was engaged in installing private generating plant and also on central-station work. From 1894 onwards he was in business on his own account, undertaking private-plant installation work, but returned to Messrs. Edmundsons in 1896 as an assistant engineer. He was appointed in 1898 as engineer and manager of the Salisbury Electric Light Co., being responsible for the erection of the plant and later for its operation and management. Rejoining Messrs. Edmundsons in 1900, he was engaged in designing, and supervising the erection of the plant for, a number of electric supply undertakings, until his appointment in 1907 to the position of engineer and manager of the Cornwall Electric Power Co., which he held until his retirement in 1934 owing to ill-health. He was elected an Associate of The Institution in 1896 and a Member in 1919.

ARTHUR PIRRIE HASLAM, who died on the 5th February, 1940, at the age of 74, was in his early days laboratory assistant and science master of the King Edward Grammar School, Birmingham. He then joined in October, 1884, Messrs. Woodhouse and Rawson and was in charge for several years of various processes in the manufacture of glow lamps. During this time he studied electrical engineering at Finsbury Technical College. Later he was engineer-in-charge of the firm's electrical plant, and subsequently assistant engineer on special work such as testing new inventions, etc. At this period he was a frequent contributor to the electrical Press, and was in active co-operation with Prof. Silvanus Thompson in the preparation of the latter's well-known work "The Electromagnet."

In September, 1893, he was appointed assistant in the estimating department of the Brush Electrical Engineering Co. and eventually took charge of that department. In August, 1902, he was employed by Messrs. Mordey and Dawbarn as assistant engineer.

He was among the pioneers who introduced electric portable tools into this country and did a great deal to popularize the use of these labour-saving devices, particularly in the shipbuilding industry. In 1913 he founded the Westminster Tool and Electric Co., which in 1937 became Westool Limited. After producing electric tools for some years, for the last 15 years of his life he devoted his entire energies to the design and production of standard coils for the electrical industry. His activities covered a very wide area and, since his passing, numerous tributes have been paid by engineers and designers in all parts of the country to his unstinted

help and valued advice in the development and production of apparatus in which electrical coils were employed. Within a few days of his death he travelled from London to Glasgow to advise on a problem connected with control gear for important machine tools urgently needed for the national effort.

He was elected an Associate of The Institution in 1888, an Associate Member in 1899 and a Member in 1906.

G. R. H.

PROFESSOR CHARLES FREWEN JENKIN, C.B.E., F.R.S., LL.D., died at St. Albans on the 23rd August, 1940. Born in 1865, he was the second son of Fleeming Jenkin, at one time professor of engineering at Edinburgh. Like his father, he followed in later life an academic career, being elected in 1908 the first professor of engineering science at Oxford, where he remained until 1929. He was educated at Edinburgh Academy and Edinburgh University, and studied engineering for 3 years at Trinity College, Cambridge. In the course of his career as a practical engineer he was for 10 years with Messrs. Siemens Brothers, working both in London and, later, as manager of the works at Stafford. Early in the war of 1914-18 he joined the Navy, and when the R.F.C. and the R.N.A.S. were amalgamated he was given the rank of lieutenant-colonel and placed in charge of the department dealing with aircraft materials. He was awarded the C.B.E. in 1919. After the war he returned to Oxford, where he devoted himself to research work dealing with fatigue failure of metals and building materials. He resigned his chair at Oxford in 1929 in order to give his whole time to experimental work, much of which was carried out at the Building Research Station, Watford. In the earlier part of his life he took up botany and zoology as a recreation, becoming an authority on sponges. He was elected an Associate of The Institution in 1899 and a Member in 1901.

MAJOR ARTHUR EVERARD LEVIN, T.D., who was born on the 17th February, 1872, and died on the 8th November, 1939, received his early education privately. He then took a course of electrical engineering at the School of Electrical Engineering, Hanover Square, and subsequently attended evening classes at Finsbury Technical College. He began his practical training as a premium pupil and improver with the Brush Electrical Engineering Co. from August, 1887, to December, 1890. He was then employed as a draughtsman and as an assistant engineer by Oerlikon, Ltd., and Brown, Boveri and Co., respectively. In 1899 he was appointed assistant European agent for the Brill Co. of Philadelphia. He resigned, however, early in the following year to enlist as a sapper in the London Electrical Engineers Volunteers and served in the South African war, supervising electric lighting work in Pretoria and Johannesburg. From October, 1901, to August, 1914, he was chief assistant engineer in the employ of Messrs. Mordey and Dawbarn, consulting engineers, Westminster, and was engaged on the preparation of estimates and schemes for electric lighting and traction work. During the Great War he served in the Royal Engineers, first as Captain and subsequently as Major, and he was mentioned in dispatches in April, 1918.

After demobilization he returned to consulting work, retiring from the profession in 1928. His chief interest in later years was astronomy, more particularly in connection with computations, and he was a director for many years of the Computing Section of the British Astronomical Association, devoting much time to the preparation of the annual "Handbook."

He joined The Institution in 1890 as a Student, and became an Associate in 1893, an Associate Member in 1899 and a Member in 1918.

VERNON LINDOP was born at Birmingham on the 31st March, 1871, and was educated at King Edward's Grammar School, Birmingham. He went to Argentina in March, 1888, and entered the service of the River Plate Electricity Co. at La Plata. In 1892 he erected the company's electric light station at Tres Esquinas. In 1895 he transferred to Tucumán as manager, and erected the power station in that city. In 1900 he returned to La Plata as managing director and chief engineer, and subsequently as chairman of the local board, until the absorption of the company in 1923 by the Cia. Hispano-Americana de Electricidad. Later he was for some 5 years chairman of the local board of the La Plata Tramways Co. During a critical period of the war of 1914-18 he was local managing director of the Forestal Land, Timber and Railways Co.

He was a most efficient organizer of all community activities and was instrumental in bringing about close co-operation between all the institutions with which he was associated in Argentina. He was the first Chairman of the Argentine Local Centre and served on the Committee for a number of years, and he was conspicuous as one of the moving spirits in fostering the activities of the Centre in its early days. He maintained an active interest in the Centre almost up to the time of his death, which occurred on the 7th July, 1939. He was elected an Associate of The Institution in 1898, an Associate Member in 1899, and a Member in 1900.

R. G. P.

SIR OLIVER LODGE, D.Sc., F.R.S., died on the 22nd August, 1940, in his 90th year. His death deprives us of a kindly leader, and it recalls innumerable successive phases of the advance in physics that he strove to elucidate and to enthrone in the realm of hypothesis. At a critical stage of his life, when natural knowledge became for him too circumscribed, he sought adventure in an abstruse field of research where evidence was more difficult to analyse and to appraise than had been the case along the normal path of repeated observation and measurement that had led him to success in his early physical investigations. Although his activities were, by this digression, somewhat diverted, he never lost his hold upon what the laboratory and mathematical science could reveal of the material universe. In whatever direction his work might take him, he exerted gracious influence. Better than any man of his time, he could put into a few crisp phrases the essentials of a recondite argument that would charm a mixed audience into attention and win their approbation and their smiles.

He was born on the 12th June, 1851, at Penkhull, near Stoke-on-Trent, the eldest son of Oliver Lodge of Wolstanton, who gave him the additional name Joseph.

The lad was sent to Newport Grammar School until he was 14, when he found a place in industrial life with his father. With a strong bent for learning, but with no opportunity for obtaining the advantages of instruction in a residential university, he climbed step by step up the ladder provided by the University of London, early gaining first-class honours in physics. Ultimately he abandoned the idea of a business career, and entering University College, London, took his degree of D.Sc. in June, 1877.

Following upon this success, he was appointed assistant professor at University College. He also gave lectures on physics to young women, at Bedford College, which at that time was in York Place, Baker Street. The college possessed a gold-leaf electroscope, a Leyden jar, and some primitive apparatus for demonstrating hydrostatics; and in an adjacent room Pickering had made an excellent beginning with a corresponding chemical laboratory. In 1881, however, Lodge was called to Liverpool, and his lectureship at Bedford College passed into the care of Prof. F. D. Brown, of Oxford. From Liverpool, he transferred his activities, in 1900, to Birmingham, as principal of the new university of that city. In 1919 he relinquished his professorial work and made his home at Normanton, near Salisbury, a centre for literary labour and scientific and other research.

A cardinal event in his career was his discourse on the 1st June, 1894, at the Royal Institution, on wireless telegraphy. The untimely death of Heinrich Hertz in January of that year, at the early age of 37, had cast gloom over the scientific world. Lodge paid a high tribute to him and proceeded to expound the principles of wave transmission that Hertz had demonstrated. He described briefly the apparatus that Hertz had constructed, including the radiator and the receiver, and referred to his own experiments that followed. This discourse was published, with additions, in his "Signalling through Space without Wires." He explained that transmission of electrical waves through wires had been known for several years, and that the special discovery by Hertz in 1887 and 1888 was transmission of such waves through free space.

In 1889, there appeared his "Modern Views of Electricity," his most valuable contribution to electrical literature. It was a review of the state of knowledge and speculation, at that time, concerning conduction, radiation, magnetism and the constitution of matter, related to ether theory and the phenomena of radio activity. There was then, as now, a demand for a mechanical model of the universe. Things were precisely as P. G. Tait had depicted them in 1880 when he complained that no experimenter had yet verified the existence of "that wonderful elastic jelly which we *know* must fill all space without offering perceptible resistance to bodies moving in it—that jelly whose inconceivably rapid quivering is the mechanism by which comes to us continuously from the sun that supply of energy without which life must at once cease from the earth." It had been an object of Clerk Maxwell to reduce electric and magnetic phenomena "to stresses and motions of the ethereal jelly," and towards this end Lodge shaped his course.

Immediately following upon the discovery of the

transmission of electric waves through free space, Hertz was approached by his contemporaries and was asked if his results could be applied to signalling. In 1889, Hertz wrote to Huber and pointed out that the application would require a mirror as large as a continent. To Lodge, however, the difficulties did not appear to be insuperable; it is recorded by Campbell Swinton that, in 1894, at the lecture at the Royal Institution, Lodge "went so far as to ring a bell by this means from one end of the building to the other, through the thickness of several partition walls." Moreover, it was Lodge who applied the name "coherer" to a loose-contact device that exhibits the phenomenon of contact-making by a spark, a phenomenon that was already familiar to David Hughes.

The same circumstances throw light upon the sequence of discoveries with regard to "tuning." In his investigation of detectors and for his wavelength measurements, Hertz of course tuned his circuits, but he left it to Lodge and others to apply tuning to signalling and to telegraph circuits for wireless transmission. The part that Lodge, Muirhead and Robinson took in this development is stated by Sir Ambrose Fleming in "The Principles of Wave Telegraphy and Telephony." It may be remarked that Robinson, who had long acted as an assistant to Lodge, had been trained in laboratory arts in the physics and chemistry laboratories at Coopers Hill College, as an assistant to Prof. Herbert McLeod, F.R.S., one of the most skilful manipulative physicists since Michael Faraday.

As an example of the work of Lodge in electrochemistry, there is his apparatus for demonstrating the migration of ions. It consists of a horizontal glass tube with turned-down ends dipping into separate beakers of dilute acid. The tube is filled with jelly dyed with phenolphthalein. When a current is passed, hydrogen ions from an anode discolourize the dye, and a boundary surface is seen to advance along the tube. Of his further activities, it suffices to remind ourselves of his numerous contributions to our *Journal*, particularly his two Kelvin Lectures in 1914 and 1928 respectively, and to direct attention to references to him in the "History" of our Institution. He was elected a Member in 1889, a Vice-President in 1902–1904, and an Honorary Member in 1924; and he received the Faraday Medal in 1932. He was Chairman of the Birmingham Local Section (now South Midland Centre) in 1902–1904.

It is in his two small books, "Atoms and Rays" and "Advancing Science," that he tells of his varied achievements and of his association with his contemporary pioneers. There is an account of his early investigation of "dust" that brought him into prominence, and a running commentary upon the work of the British Association, to which, from 1870 to 1931, he so effectively contributed.

He was elected a Fellow of the Royal Society in 1887 and was knighted in 1902. He was Romanes Lecturer at Oxford in 1903, president of the Physical Society in 1899–1900, and of the British Association in 1913. In 1877 he married Mary, the daughter of Alexander Marshall; she died in February, 1929. They had six sons and six daughters. His brother Alfred, the mathematician, was known to electrical students of the last

century for his work on hyperbolic functions. A Memorial Service to Sir Oliver Lodge was held at the church of St. Margaret, Westminster, on the 3rd September, 1940. And thus he rests from his labours.

R. A.

PETER VALENTINE McMAHON died on the 14th September, 1940, at the age of 72, after a life particularly identified with London tube railways, of which he was a pioneer. He was born at Dundalk and was educated at the Christian Brothers Schools and St. Mary's College. From the age of 16 he served an apprenticeship for 3 years with the Dundalk Ironworks Co. He then proceeded to London and became a student at the City and Guilds Technical College, Finsbury, where he studied under Prof. Silvanus Thompson and Prof. Perry. At the completion of the course he was awarded the college certificate and first prize in electrical technology. For a short time after leaving Finsbury he was engaged on the electrical installation at Earl's Court Exhibition, after which he was resident engineer at the Waterford electricity supply station, where he was responsible for the installation of alternating-current generating plant for Messrs. Laing, Wharton and Down. This appointment he held for only a comparatively short time, and in 1890 he returned to London to act as resident engineer for Messrs. Mather and Platt in connection with the electrical equipment of the deep-level railway, known as the City and South London Railway, which was then being constructed between King William Street in the City and Stockwell. Thus commenced his life-long connection with London's tube railways. For the City and South London Railway he was responsible for the installation of the electrical equipment and for a considerable amount of its design, many new problems having to be faced. When the line was opened he was appointed assistant engineer to the railway company. In 1896 on the retirement of Mr. (afterwards Sir) Basil Mott from the position of engineer to the company McMahon succeeded him. When the line was extended in 1901 to Moorgate and Islington, and in 1907 to Euston, he acted as consulting engineer in connection with the electrical equipment and rolling stock. In 1912 he became, on the amalgamation of the tube railways, superintendent of electric power at the Lots Road power station of the London Underground Railways system, and he continued in this position under the London Passenger Transport Board until 1927, when he became assistant chief electrical engineer to the Board. He retained this position until his retirement in 1933.

About 1894 he investigated the behaviour of cores of different sizes and shapes in a solenoid and the results of the research were published in the *Electrician*. This research was undertaken with a view to developing a satisfactory electrical means for operating signals, which were then wire-operated. The apparatus he produced was the forerunner of the automatic signal. He also contributed various other articles to the technical Press from time to time.

He became an Associate of The Institution in 1889, was elected a member in 1895, and served on the Council from 1910 to 1913. In 1899 he read a paper on "Electric Locomotives in Practice, and Tractive Resistance

in Tunnels" (*Journal I.E.E.*, vol. 28, p. 508), for which he was awarded the Institution Premium; and in 1904 he was awarded the Willans Premium for his paper entitled "City and South London Railway; Working Results of the Three-Wire System applied to Traction" (*Journal I.E.E.*, vol. 33, p. 100). This paper described the 3-wire direct-current system with 2 000-volt distribution to the substation, which he had introduced and which he described as in reality "a sort of 5-wire system."

He was well known for the active part he took in social functions of electrical engineers, and his guidance of many of them will be much missed. He, together with A. M. Sillar, J. E. Kingsbury and T. E. Gatehouse, were the founders of the Electrical Engineers' Ball.

E. W. M.

WILLIAM HENRY MASSEY, M.V.O., who died on the 13th May, 1940, in his 92nd year, was one of the pioneers of electrical engineering. He was born on the 1st October, 1848, at La Seyne, near Toulon, France, where his father was an engineering contractor. He obtained his early education partly in France and partly in Russia, and completed his education at Leeds Grammar School. He then became an apprentice in the Abbey Street Millwright Co. of Leeds. After serving as engineer on a ship of the Russian Steam Navigation Co. he was appointed outdoor manager of Messrs. John Penn and Sons, marine engineers. He became recognized as an expert in marine engineering and as a result accepted in 1875 an appointment in Berlin with a firm of German marine engineers. Two years later he returned to this country and shortly afterwards was employed by Messrs. John Fowler and Co. as outside manager. In that capacity he had occasionally to consider the question of electric lighting plant. In 1881 he became general manager of the Electric Light and Power Generator Co., but shortly afterwards set up in business on his own behalf as a consulting engineer and was associated with the installation of electric lighting in 1882 in the Crystal Palace. He was also responsible for the installing of electric light in Windsor Castle and Buckingham Palace, and was appointed as mechanical and electrical engineer to the Royal Household, a position which he held for more than 40 years. For many years he was also a director of the Brush Electrical Engineering Co. He was elected an Associate of The Institution in 1881 and a Member in 1884. In the latter year he read a paper before The Institution (then the Society of Telegraph Engineers) on "A Train-Lighting Experiment," in which he described the experimental van containing a boiler and generating plant which was tried for a few months on the Metropolitan District Railway between High Street, Kensington, and Putney Bridge. Fifty Swan lamps were installed in the train, and the experiment was very successful. He was also a founder member of the "Dynamicables."

CHARLES H. MERZ, D.Sc., was killed, with his son and daughter, during a night air raid on the 15th October, 1940. Born at Gateshead-on-Tyne in 1874, he early showed promise of exceptional qualities of imagination, sound judgment, organizing ability and decision which,

combined with great engineering genius, were destined to lead to one of the most brilliant careers in the field of applied electricity. He grew up in an intellectual atmosphere; his father, Dr. J. Theodore Merz, was an industrial chemist by profession but had wide business, scientific and literary interests and acquired an international reputation as a philosopher; his mother was a sister of Wigham Richardson the shipbuilder, and his uncle, Dr. R. Spence Watson, was a famous public figure in the North of England who influenced him greatly.

Owing to his mother's Quaker connections Merz was educated at Bootham and, after attending Armstrong College, went in 1892 as a pupil at the Pandon Dene generating station of the Newcastle-upon-Tyne Electric Supply Co., which had been formed in 1889 by Dr. Spence Watson and Dr. J. T. Merz. In 1894 he became a pupil at Robeys of Lincoln. He then went to work at Bankside for the newly established British Thomson-Houston Co., of which his father was at that time a director. When the B.T.H. obtained the contract for providing electricity supply in Croydon, Merz acted as chief assistant to A. L. C. Fell for the construction work and, on completion of this, was appointed at the early age of 23 as manager and engineer to operate the plant and develop the sale of electricity. So successful was he in this that he was given charge of a similar but larger contract at Cork which also included the tramways. Here he first met William McLellan, with whom he was to be so closely associated until the latter's death in 1935.

While at Cork he was asked, at the suggestion of his uncle, Wigham Richardson, to assist the Walker and Wallsend Gas Co. with a Parliamentary Bill for establishing an electric power supply for the shipyards and industrial works on the Tyne. On the necessary powers being obtained, he was appointed consulting engineer for the scheme and took McLellan with him to Newcastle-upon-Tyne. Here they designed the Neptune Bank power station, which was inaugurated by Lord Kelvin in 1900 and was the first in this country to generate 3-phase current—at what was then the high voltage of 5 500. This pioneer electric power supply undertaking was shortly afterwards transferred to the Newcastle-upon-Tyne Electric Supply Co. and the Carville power station was soon begun to deal with the rapid increase in demand. Under Merz's guidance this company and its sister companies (now all combined into the North-Eastern Electric Supply Co.) rapidly expanded during the next 7 years to cover the whole of the North-East Coast. This involved much Parliamentary work on the early Power Bills, during which Merz proved his quite exceptional ability as an expert witness.

This ability was conspicuously shown during the protracted proceedings on the Administrative County of London Electric Power Supply Bill in 1905. Although he enlisted influential support, this first proposal for consolidating the chaotic London position was entirely Merz's own conception based on his pioneer work in electric power supply on the North-East Coast. His masterly handling of the whole scheme is still remembered by many as a *tour de force* by a young man of 31 who came up from the provinces and pitted himself against many of the leading engineers of that time.

After passing all Committee stages the Bill failed through lack of Parliamentary time, but it was characteristic of Merz's equable temperament never to let such disappointments affect his work, although he always felt that nationally a great opportunity had been lost. Further attempts were made by him and others in subsequent years, culminating in that of the London County Council in 1914 based on an extensive report which Merz prepared for them. War, however, intervened and it was not until 1925 that a partial solution was effected by the grouping of the East End and West End companies, in which Merz was associated with the East End group, having previously been retained by Sir Harry Renwick for the design of the Barking power station on the site which Merz had originally scheduled to his 1905 Bill.

In 1899 Merz had begun general practice as a consulting engineer, and in 1901 he took the late Colonel McLellan into partnership, thus starting the firm of Merz and McLellan. In 1902 Merz began his great work on railway electrification when, at the request of Sir George Gibb, then general manager of the North Eastern Railway, he supervised the electrification of the suburban lines north of the Tyne. In 1907 he visited Australia to report on the electrification of the Melbourne suburban system, the carrying out of which he was later asked to supervise in 1912. This was the beginning of a wide association with power supply and railway electrification abroad, especially in the Dominions, during which he visited Australia three times, the Argentine twice, South Africa four times, India three times and the United States seven times, as well as many other countries. These visits did much to retain for Great Britain a leading share in the large electrical developments overseas, and although Merz was sometimes criticized in some quarters for his energetic action in seizing opportunities for initiating electrical developments, he always felt that in so doing he was performing a national service. He had a keen sense of political values, unusual in an engineer, and this enabled him to interest such men as General Smuts in his proposals. His reports were invariably characterized by wide vision and boldness of conception. Two such reports led directly to the formation of the Electricity Supply Commissions of Victoria and South Africa.

Merz had an extraordinary capacity for keeping in close touch with all the details of the many large schemes which he always had simultaneously under his supervision, and also a remarkable flair for judging character and ability, as evidenced by the important positions so many of those associated with him now occupy. His absorption in the larger issues of organization and planning never interfered with his interest in purely engineering and scientific matters, and he was personally responsible for many inventions and developments in such fields as metal-clad switchgear, balanced protective gear, metering and coal distillation. He also took a leading part in applying to power station work Sir Charles Parson's developments of the steam turbine and Dr. Ferranti's ideas of higher pressures, re-heating, air heating and feed heating, and he was one of the first engineers to make extensive use in this country of overhead lines and, successively, of 20-, 33-, 66- and 132-kV

cables. His pioneer work on the North-East Coast in the use of waste heat in conjunction with power supply should also be mentioned.

Apart from his direct war work Merz devoted much attention during the years 1914–1918 to the need for re-organizing electricity supply in Great Britain and was chairman of the Electric Power Supply Sub-Committee of Lord Haldane's Coal Conservation Committee. He was a member of the Williamson Committee and was closely associated with the setting up of the Electricity Commissioners. In 1924 he prepared a scheme which visualized what is now the "Grid," and resulted in the appointment of the Weir Committee before which he was the first witness.

With such a varied career it is difficult even to summarize his many activities, but reference must be made to the important work which he did towards the end of the last war in organizing for the First Lord, Sir Eric Geddes, the new Department of Experiment and Research at the Admiralty. He was its first Director, and during this later period of the submarine menace the "Asdics" were developed.

In The Institution Merz will be remembered for the classic paper he and McLellan gave in 1904 on "Power Station Design," based on their pioneer work at Carville.

He joined The Institution as a Member in 1902 and was a Vice-President from 1912 to 1915, but his reticence over public speaking restrained him from accepting invitations to be nominated for the presidency. His reserve, a certain austerity of outlook and a complete lack of interest in games or "small talk" made him difficult to know intimately, but to those who were privileged so to know him no one could have been more helpful or kindly and for them no aid in trouble was too great. His family life was a perfect example of quiet happiness and mutual trust and sympathy, with a deep spiritual background. These characteristics, combined with a distaste for public life, led him to decline the offers of many high public honours which his services to the nation brought to him, but he always greatly valued the presentation of the Faraday Medal of The Institution, the Honorary Degree of D.Sc. conferred by the University of Durham and his vice-presidency of the Royal Institution, in which he took a deep interest.

He married in 1913 Stella, daughter of Edmund de Satur of Dublin. Although their children were killed with him, Mrs. Merz escaped without permanent injury.

His son Robert—a Graduate of The Institution—had already shown promise of a brilliant career. He was educated at Harrow and Trinity College, Cambridge, and was a pupil at Brown, Boveri. He completed his training in South Africa, but returned after the outbreak of war to take up important work with the Ministry of Aircraft Production.

At the time of his death Merz had been invited by the Minister of Supply to assist him in an important capacity. His death is thus a great loss to the country's war effort as well as to the whole electrical industry. His outstanding abilities will also be sadly missed during the period of reconstruction after the war. In him we mourn the untimely loss of one of Britain's truly great men, and

one who, as Sir Richard Redmayne said in *The Times*, "had some claim to be regarded in his own sphere as the outstanding electrical engineer of his time."

J. R. B.

LORENZO WILLIAM MIGOTTI received his early education at St. Nicholas School, Plumpstead, and Merchant Taylors' School, London, and then became an apprentice with Messrs. Watson, Geisenheiner and Co., electrical engineers, London. In 1896 he went to South Africa and was engaged in general electrical and central-station work with the Cape Town Tramways and the Cape Government Railways. During this period he attended a course of evening classes at Cape Town University. Returning to this country in 1900 he was employed for a short time as electrician in the rolling-stock department of the Central London Railway. Later he was put in charge of all the electrical equipment in the locomotive department. He next took the post of general foreman with the British Thomson-Houston Co., in charge of the equipment of rolling stock for the Central London Railway and the Great Northern and City Railway. On relinquishing this post in 1905 he joined the Underground Railways of London as rolling-stock engineer, being responsible for the construction and equipment of rolling stock on the Bakerloo and the Piccadilly and Brompton Railways.

In January, 1908, he was appointed assistant construction engineer with the Buenos Aires and Pacific Railway Co., later, in April, 1911, becoming local manager at Bahia Blanca of the South American Light and Power Co. In June, 1917, he joined the Rosario Electricity Supply Co. as chief engineer. After a number of years with this company he went to La Plata to take up a position with the Compañía Argentina de Electricidad de La Plata. Some time later he returned to England. In 1926 he again went to the Argentine, to take over the management of "Ferrum" Industria Argentina de Metales. He remained as manager of this company for 8 years before he resigned in 1934 in order to go to Brazil as manager of the Para Electric Railways and Lighting Co. Owing to continued bad health he had to leave Brazil for England, where he died on the 26th August, 1939, at the age of 60.

While in Rosario he was British Vice-Consul during the war of 1914–1918, and later was chairman of the Empire and Services Club in Buenos Aires. He was also the first president of the Association of Technologists of the River Plate. Although he never played games he was an exceptionally keen supporter of athletics and outdoor sports.

He was elected a Member of The Institution in 1920 and was Chairman of the Argentine Local Centre in 1925, subsequently serving on the Local Centre Committee for a number of years.

R. G. P.

JOHN HEDLEY NICHOLSON, signal and telegraph engineer, Great Southern Railways, Ireland, was born on the 29th March, 1875, at Benton, near Newcastle-upon-Tyne. He joined the signal department of the North-Eastern Railway in 1891, and when in charge later of the Newcastle district was responsible for the installation of the original electro-pneumatic signalling

(about 9 cabins) at Newcastle-upon-Tyne in 1902-3. He went to Ireland in 1909 as signal superintendent of the Great Southern and Western Railway, and subsequently inaugurated various improvements and extensive rearrangements of signalling. In 1923 he was responsible for the introduction of electric power operation of points and signals by hand generator, of which invention he was joint patentee. A number of these hand-generator installations were subsequently installed on the Great Southern Railways in Ireland, and also in other countries. He was also joint patentee of an arrangement for the interlocking of gates and signals at level crossings.

On the amalgamation of the Irish railways in 1925, he was appointed signal and telegraph engineer to the Great Southern Railways, and in 1929 was given the status of chief officer. From time to time he was responsible for the centralization of signalling at various stations on the system, and in 1935 introduced colour-light signalling into the Irish Free State. This signalling has since been extended to all cabins in the Dublin area and suburbs. In 1939 under his supervision was completed a very fine example (76 levers) of all-electric signalling at Kingsbridge terminus of the Dublin-Cork main line. This installation completed the colour-light signalling in the Dublin area of the Great Southern Railways.

His interests outside the railway were chiefly his home and his garden. He was held in high esteem by his colleagues, and by all who came in contact with him, and his death, which took place on the 5th June, 1940, is deeply regretted. He joined The Institution in 1922 as an Associate Member and was elected a Member in 1926.

H. J. G.

GEORGE HINDE NISBETT, J.P., one of the pioneers of the electrical industry, died on the 21st October, 1940, at the age of 73. He received his technical education under Professors Ayrton and Perry at the City and Guilds Central Technical College and the Finsbury Technical College respectively, and obtained his practical training as a pupil in the firm of Paterson and Cooper, one of the earliest manufacturers of arc lamps. For that firm he installed a number of electric lighting plants, and often recalled with much pleasure the one installed for Madame Patti at Craig-y-Nos. In 1890 he served as chief assistant to Major-General C. E. Webber, who was acting as consulting engineer to the British Electric Light Co. and the City of London Electric Lighting Co., and subsequently he was appointed chief electrical engineer to the last-named company, for whom he designed and laid down the first low-voltage alternating-current distribution in this country. He also originated the free wiring system. He was among the first who recognized the merits of the paper-insulated cable and, in 1894, he joined the British Insulated Wire Co. (now British Insulated Cables, Ltd.) as chief engineer and proceeded to develop the use of paper-insulated cables for the transmission and distribution of electricity. He was appointed chief engineer and manager of the company in 1902; in 1924 he became a director, in 1928 managing director, and, later, deputy-chairman, which position he held up to the time of his death. He was also chairman of the Midland Electric Corporation for Power Distribution, and a director of a number of other

electricity supply undertakings, including the Lothians Electric Co. and the Colne Valley Electric Supply Co. He took a great interest in technical education, and his work in this connection was recognized when the honorary degree of Master of Engineering was conferred on him by Liverpool University.

He joined The Institution in 1885 as a Student, and was elected an Associate in 1890 and a Member in 1893. From 1916 to 1919 he served on the Council, and for many years between 1900 and 1929 he also served on the Committees of the Manchester Local Section, the Liverpool Sub-Centre and the Mersey and North Wales (Liverpool) Centre, being Chairman of the Liverpool Sub-Centre in 1921-22.

No notice concerning him would be complete without a reference to his great grasp of affairs, to which he brought the clear-thinking brain of a trained engineer, and, whatever his anxieties were, he always retained a considerable sense of humour. Furthermore, he was ever ready to give most generously not only advice but also material help whenever the need arose.

B. W.

LIEUT.-COL. WALTER ALFRED JOHN O'MEARA, C.M.G., R.E., died on the 6th November, 1939, at the age of 76, and his death removed from the circle of his many friends a colourful personality and a distinguished and versatile officer who had served his country in many different capacities, both military and civil.

He was of Irish extraction, born in Calcutta in January, 1863, son of Alfred O'Meara of Simla, and grandson of Thomas O'Meara of Tipperary. His first professional objective in life was the Indian Civil Service, but from this course he was more or less incidentally deflected to a military career by success in a competition for vacancies in the Royal Military Academy, Woolwich, in 1880. In March, 1885, he was posted to the Bengal Sappers and Miners, and volunteered for service in the war in Burma, in which he received 11 wounds and was left as dead by the enemy. Face wounds, associated with a broken jaw, and a mangled right hand, remained with him as permanently visible evidences of his ordeal.

After further service with the Royal Engineers at Portsmouth he was attached in 1889 to the Telegraph Battalion—later known as "K. Company"—which was at that time in charge, for the purposes of its Signal Service training, of what was known as the Southern District of the Post Office Engineering Department, embracing all the counties south of the Thames and Severn. In that capacity he took a leading part in the planning and construction of the Anglo-French telephone trunk lines between London and St. Margaret's Bay.

After 5 years' service with K. Company he was, in 1894, sent to South Africa where his services extended far beyond his nominal duties as a R.E. Signals Officer. He returned to England for the Staff College course, but in June, 1899, was ordered to South Africa and was engaged as an Observation Officer in Intelligence and Secret Service work. On the outbreak of war he was sent to Kimberley, where he remained throughout the siege, during which his fertile mind, energy and initiative were of great service in countless ways. His loyal help was acknowledged in dispatches by General Kekewich. O'Meara's book "Kekewich in Kimberley" is good

reading. Later on he occupied many important administrative positions, including that of Government Commissioner for Johannesburg, where he was, at one and the same time, Mayor, Town Council and Town Clerk. In the final dispatch of the war he was again mentioned, and was awarded the C.M.G. and the Queen's Medal with five clasps.

During a period of leave in England he was offered, and accepted, the position of assistant engineer-in-chief at the General Post Office. This appointment from outside the Service caused a certain amount of heartburning among the senior officers of the engineering staff, but this soon disappeared with experience and appreciation of his character and sincerity. When Sir John Gavey retired in 1907 O'Meara succeeded him as engineer-in-chief, a position which he held until 1912.

In many ways he left his mark on the P.O. Engineering Department. He continuously pressed for recognition of the status of engineers. He stressed the need for selecting staff recruits with scientific training and attainments, and he secured the admission of a liberal leavening of engineering university graduates each year. He encouraged the sense of personal responsibility among controlling officers. He codified the "Regulations" of the Engineering Department. He introduced the statistical systems of unit costs for construction and maintenance work which has done so much to enable the Department to improve its efficiency. He moved K. Company of the Royal Engineers from Southern England to Ireland, which was a much more suitable terrain for its telegraph training. With great skill and tact he handled a proposal by the Post Office Engineers to form a Society which would have been a kind of trades union, and he transformed the project into one for a purely scientific and technical Association—"The Institution of Post Office Electrical Engineers." But he chafed increasingly under the restrictions of secretarial and Treasury control of his technical and administrative activities. Although his attitude actually led to his severance from the Post Office, it undoubtedly contributed to the greatly improved administrative conditions which came into being in later years.

He obtained leave to retire from the position of engineer-in-chief in 1912, but for a further year he acted as "Special Engineering Commissioner" with the mission of inspecting and reporting on the telephone systems of the United States and the Scandinavian countries. When he finally left the Post Office in the autumn of 1913, in his 51st year, he turned to the legal profession and speedily qualified as a barrister-at-law.

The outbreak of the Great War in 1914 again deflected his activities into military channels. He served as G.S.O.2 at Chatham, and later in Norfolk, where he received the brevet of Lieut.-Colonel.

He joined The Institution as an Associate in 1890 and was elected a Member in 1903. He served as a Member of Council from 1908 to 1911, and as a Vice-President from 1911 to 1913. At the conclusion of the Great War he was asked by the Council to act as editor of the Institution's Roll of Honour, containing biographical notices of each of the 162 members who lost their lives in the war. This work occupied him for 5 years. Among his other services to The Institution was that of assisting

the late Attorney-General, Sir Thomas Inskip (now Lord Caldecote), in the proceedings before the Commissioners of Inland Revenue, which succeeded in securing for The Institution immunity from income tax. In his later years he interested himself in many good causes and in literary activities.

O'Meara was a man of unblemished rectitude, with the highest standards of honour and duty, a fearless and uncompromising follower of what he felt to be right, and in few men has the flame of unselfishness burned more purely. He never shirked an unpleasant task. He had a horror of weakly taking the line of least resistance and, indeed, one had now and then to suggest to him that he seemed to be deliberately choosing the line of greatest resistance. At the many international conferences which he attended as principal British delegate he always earned warm appreciation, alike for his ability and his pleasant and debonair camaraderie. He took the cares of office very seriously, but in moments of relaxation he was invariably an entertaining and charming companion.

He married in 1892 and is survived by his widow. Their only son received a commission in the East Lancashire Regiment and was killed in France in February, 1917.
T. F. P.

ISAAC HARDY PARSONS was born on the 29th November, 1868, and was educated at Wiggston School, Leicester. After serving a 5-years' apprenticeship with Messrs. Gent and Co., Faraday Works, Leicester, he became, on the 1st January, 1890, a partner in the firm. In 1903 the firm became a limited company and he was appointed joint managing director, and later, on the death of his colleague in 1917, sole managing director, a position which he held until his death on the 31st August, 1940. From 1890 he was in charge of all the technical work of the firm, including the design of small-current apparatus such as mining and railway signals, water-level indicating apparatus, industrial telephone systems and electric clocks. In particular he was responsible for the design, manufacture and installation in 1910 in the Liver Building, Liverpool, of what was claimed to be the largest clock in the world. He was elected a Member of The Institution in 1928.

GERALD WILLIAM PARTRIDGE died on the 3rd May, 1940, aged 75. He was born on the 22nd June, 1864, and received his technical training at the Hammond College. After serving an apprenticeship with the Anglo-American Brush Co., in 1888 he entered the service of the London Electric Supply Corporation at the Grosvenor Gallery generating station, and his association with that company lasted over 50 years. In the early days of electricity supply he was responsible for a number of important inventions, including the oil switch, the spark-let fuse, and the use of a telephone receiver for detecting faults on concentric cables. He was on the staff of the Deptford Station of the London Electricity Supply Corporation for many years, and was then appointed chief engineer and manager of the undertaking. During the war of 1914-18 he was director of the Metropolitan Munitions Committee, while at the same time continuing his work at Deptford. With the late Sir Alexander

Kennedy he became joint chief engineer to the London Power Co., later serving as chief engineer until the appointment of Sir Leonard Pearce in 1926. He retired from his position as manager to the London Electric Supply Corporation in 1931, but remained a director of the undertaking up to the time of his death. He was also a director of the British Power and Light Corporation, the North Wales Power Co., and the Calcutta Tramways Co., as well as of a number of smaller electricity supply undertakings.

Elected an Associate of the Institution in 1891, he became a Member in 1896, and served as a Member of Council in 1906-9, 1914-17 and 1923-26, and as a Vice-President from 1917 to 1920.

His early experiences in the electricity supply industry were described in a paper read at the I.E.E. Commemoration Meetings in 1922 and published in Vol. 60 of the *Journal*. He had the almost unique record of serving one company for 50 years.

Partridge was one of Ferranti's young men and was truly among the pioneers of public electricity supply. The tale of Ferranti's foresight and courage in planning the Deptford power station, in designing the alternators and the 10 000-volt trunk main, and in arranging their manufacture has often been told. It is doubtful whether the wonder of that great work is fully appreciated by more than a very few. Partridge was one of a numerous company concerned directly or indirectly in that work; it includes Frank Bailey, Stuart Bain, A. F. Berry, Lord Crawford, J. W. Drew, P. W. D'Alton, Keith Elphinstone, J. Staats Forbes, W. C. Hawtayne, Francis Ince, H. W. Kolle, Coutts Lindsay, G. H. Nisbett, Charles P. Sparks, Lord Wantage, Reginald Wilson, C. H. Wordingham, Arthur Wright and many others.

Partridge was a most amusing companion, with the useful gift of descriptive talk; his slight hesitation in speech added a characteristic touch. When he reported an event, whether an appalling accident or a joyful occurrence, the accident really was appalling and the occurrence really joyful. He had a fine repertoire of stories of various sorts and the capacity to use them sparingly. These attributes and his charm of manner made Partridge a most popular guest at any gathering of his friends and he was very well known at convivial engineering meetings, such as those of Faraday House Old Students' Association, the Batti-Wallahs and the Dynamicables. He was President of the Batti-Wallahs in 1927, and worked very hard for their welfare, and it is certain that the society owes a great deal to him.

He was a fisherman and a game shot and fond of riding; he talked well and with understanding of country life.

J. S. H.

ALEXANDER DICK PHILLIPS received his early education at Kirkcaldy High School, Fife, proceeding thence to Herriot Watt College and Edinburgh University. He began his career by serving as an apprentice with Messrs. Philp and Sons, mechanical engineers, Kirkcaldy, and later became assistant manager of the Fife Electricity Co.

In 1913 he went to Ilkeston on being appointed general manager of the Derbyshire and Nottinghamshire Electric Power Co. At that time this was a small

undertaking, but under his guidance it developed into one of the most important undertakings in the country. He was also a director of the Leicestershire and Warwickshire Electric Power Co. and the Midland Electric Light and Power Co., and manager of the Tamworth District Electric Supply Co. Among other appointments which he held was that of chairman of the Electrical Engineering Advisory Committee, Nottingham University, and chairman of the Nottingham Branch of the Electrical Industries Benevolent Association. In addition to his extremely busy business life he found time to take an active part in many public welfare organizations.

He joined The Institution as an Associate Member in 1909 and was elected a Member in 1920. He served on the Committee of the East Midland Sub-Centre for many years and was Chairman of the Sub-Centre during the session 1929-1930. His death occurred suddenly on the 31st July, 1940, at the early age of 59. J. N. R.

CHARLES FARADAY PROCTOR, who died at Chiswick on the 4th May, 1940, at the age of 79, was a great-nephew of Michael Faraday and was one of the last remaining pioneers of the development of the electric incandescent lamp.

He was born in Newcastle-upon-Tyne on the 16th February, 1861. After being educated in his native city and serving his apprenticeship with Messrs. Henry Watson and Sons, he entered the private laboratory of the late Sir Joseph Swan. There he assisted in the development of the carbon-filament lamp. In 1881 he went to Paris in connection with the fitting up of the first incandescent electric lamp factory in France and was appointed assistant manager of it. After returning to England for a period, during which he designed improved machinery for the Swan works in the North of England, he went to Lille as manager of a factory there. In 1888, when the Edison and Swan continental companies were amalgamated and became known as La Compagnie Générale des Lampes Incandescentes, a new factory was erected at Ivry-sur-Seine of which he was given control. In recognition of his development work during this period he was awarded a bronze medal at the Paris International Exhibition in 1889. In the same year he returned to England as assistant manager of the Ponders End works of the Edison and Swan Co., shortly afterwards becoming manager of their fittings department. In 1900 he was transferred to their Benwell works as assistant manager, where he remained until 1914. After joining the General Electric Co. as central station engineer at Cardiff in 1914, he was transferred in 1916 to the Osram Robertson Lamp Works, and later, in 1925, to the Research Laboratories of the company at Wembley. There he remained until his retirement, in 1931, after completing 50 years in close connection with the lamp industry.

During his active career he introduced many improvements into the manufacture of electric lamps. Among these were an improved form of vacuum pump enabling the lamps to be more readily exhausted, the present method of constructing incandescent lamps in which the filament is mounted on a flanged tube of glass which is afterwards sealed into the bulb, and the present design of bayonet lampholder.

He was elected a Member of The Institution in 1894 and served on the Committee of the Newcastle Local Section (now North-Eastern Centre) for many years, being Chairman in 1910-11 and Hon. Secretary from 1905 to 1910. R. F. P.

ALEXANDER BRUCE ROBERTSON, Jun., D.S.O., died at Aberdeen on the 24th January, 1940, at the age of 62. Although he did not appear much in the public eye, he figured prominently in the business life of that city. His associates knew him as a man who brought to business an enterprising spirit and shrewd judgment.

After serving his apprenticeship as an electrical engineer with his father, he went to London to gain a wider electrical experience. Returning to Aberdeen he entered into partnership with his father in the firm of Messrs. A. B. Robertson and Son.

In the Great War he gave distinguished military service. Before the opening of hostilities he had been prominent in the Territorial Army, and at the outbreak of war he held the rank of Major. Early in 1915 he went to France with his company, where he won the D.S.O. and was mentioned in dispatches. He retired from the Army with the rank of Colonel.

Back in civil life he quickly became one of Aberdeen's outstanding business men. Under his control his firm developed considerably, undertaking important contracts in the building of new cinemas in Aberdeen and being also responsible for work at Balmoral Castle.

His business interests were, however, not confined to his firm. He was associated in the management of many concerns and there have been few business enterprises in Aberdeen in recent years in which he was not interested. The companies with which he was associated show how varied were his business interests. He was always ready to give his financial support and the benefit of his long and varied business experience to new undertakings, or to bring new life to companies.

He joined The Institution as an Associate in 1902 and was transferred to full membership in 1922. A. L.

THOMAS ROLES was born in Brighton on the 27th June, 1875. He received his technical education at the Brighton Technical School, and his first engagement commenced in June, 1891, with the Brighton branch of the Electrical Supplies and Fittings Co., one of the late Mr. Robert Hammond's companies. In September, 1892, he entered the service of Messrs. Crompton and Co., being engaged on the erection of the original plant at the works of the Hove Electric Lighting Co., after which he was transferred to the staff of that company. Between March, 1895, and March, 1904, he held successively positions as assistant electrical engineer at Aberdeen, draughtsman and mains engineer at Leicester, and generating engineer at Poplar, leaving the last-mentioned undertaking to become chief assistant electrical engineer to the Bradford Corporation. On the 1st February, 1907, he succeeded the late Mr. Blackman in the position of city electrical engineer, which he continued to occupy until his retirement on the 26th June, 1940, on reaching the age of 65.

He was responsible for the installation of the whole

of the 3-phase generating plant at the Bradford power station, the plant having a total capacity of over 100 000 kW. An interesting feature of the power station is a large boiler working at a pressure of 1 100 lb. per sq. in. and a pass-out turbo-alternator of 2 500 kW capacity operating in conjunction with it, these units having been in service for over 10 years. A 33-kV system of transmission was also laid down during his connection with the Bradford undertaking.

Bradford being a big centre of the woollen and worsted textile industry, Mr. Roles was keenly interested in the electric driving of textile factories, and soon after his appointment as chief he introduced charges for electricity designed to encourage the taking of public supplies for this purpose. He also did much to stimulate domestic electrification and was one of the earliest members of the body known as "The Point Fives," which was established about 30 years ago by the engineers and managers of undertakings supplying electricity for domestic purposes under rates embodying a charge of $\frac{1}{2}$ d. per unit.

In 1901 he was elected an Associate Member of The Institution and in 1912 a Member, and he served on the Council from 1921 to 1924. He was Chairman of the Yorkshire Centre (now North Midland Centre) in 1914-15 and 1929-30. In addition, he served for 16 years on the Council of The Incorporated Municipal Electrical Association, and was President in 1919-20 and Honorary Treasurer from 1935 to 1937. He was a member of a number of committees formed in the past 25 years for the purpose of giving consideration to methods which might be adopted for the co-ordination of the supply of electricity in Great Britain, and he had a seat on the National Consultative Committee, appointed by the Central Electricity Board, from the time of its inception to the date of his retirement.

A severe attack of influenza in 1918 left him with valvular disease of the heart, and since then he had from time to time been in indifferent health. Despite that he was invariably cheerful and was a welcome figure at meetings and functions of organizations associated with the electrical industry. In the past few years, however, his health did not permit of his frequent attendance at such gatherings.

He died suddenly on the 9th September, 1940, that is, little more than two months after he had ceased to hold office, and it is greatly to be regretted that he was not spared to enjoy a richly-deserved lengthy period of retirement. He leaves a widow, to whom the members extend their deepest sympathy in her bereavement.

W. D.

LESLIE GERALD HUNT SARSFIELD, D.Sc.(Eng.), was born at Bristol on the 12th July, 1896, and died in London on the 17th September, 1940. Educated at Fairfield School, Bristol, he studied electrical engineering at the University of Bristol, where in 1915 he took the degree of B.Sc.(Eng.), proceeding later to the degree of Doctor of Science. On leaving the university he went to the British Thomson-Houston Co.'s works at Rugby and was engaged in testing all types of a.c. and d.c. machines, transformers and control gear. In 1918 he was appointed a technical assistant at the Signals

Experimental Establishment (Royal Engineers), Woolwich, carrying out experimental work on wireless receiving and transmitting equipment. From November, 1918, to June, 1920, he was again at Rugby, this time as a design engineer in the transformer department of the British Thomson-Houston Co. Returning to London, he became assistant to the technical manager of the Morgan Crucible Co.

In January, 1921, he joined the Directorate of Radiological Research, Research Department, Woolwich. For many years he was in charge of the section concerned with electrical X-ray apparatus, and he designed and constructed many X-ray transformers both for routine work and for special experimental purposes. Some months before his death he ceased to specialize in X-ray work because he was promoted to be chief engineer of the Research Department, where his activities had a wider scope than hitherto.

Elected a Graduate of The Institution in 1922, he became an Associate Member in 1925 and a Member in 1930. In 1929 he was awarded the Ayrton Premium for his paper on "The Electrical Equipment of X-Ray Apparatus."

He was the author of "Electrical Engineering in Radiology"—a book that is now recognized as the standard work on the subject.

He was a man of brilliant ability, which he applied with exemplary thoroughness in all his activities. His singular charm of manner endeared him to all his colleagues to a degree that could be described as unique. His premature death is a very great loss indeed, not only to his personal friends and colleagues but to the Services and to general scientific research.

V. E. P.

HORACE FRANCIS SIMON, who died on the 18th November, 1939, aged 70, was educated at the International College, Isleworth, and at the City and Guilds College, South Kensington. From 1891 to 1892 he was chief engineer in Key's Electrical Co., London. He then went to Germany and was employed as assistant engineer by the Union Elektrizitäts Gesellschaft at Hamburg, subsequently going to Berlin as a journalist. In 1904 he returned to London and became a partner in the firm of Newman, Wilkinson and Co. In 1906, when Electrical Installations, Ltd., was formed he was appointed a director, and later managing director, a position which he held until 1925 when he founded Electricity Services, Ltd. His association with that firm continued actively up to the time of his death. He was also for many years a director of the British Electrical Export Co. He was the inventor and patentee of "Typerlite" adjustable lighting fittings. He joined The Institution in 1913 as an Associate Member and was elected a Member in 1928.

F. J. B.

ROGER THOMAS SMITH, B.Sc., died on the 28th April, 1940, aged 77, and thereby the engineering profession lost a distinguished member. He was the son of Prof. T. R. Smith of University College, London, and was educated at that college and at Mill Hill School. He served his pupilage in mechanical engineering with Messrs. Hawthorn, Davey and Co. of Leeds, and was later employed by them on the erection of pumping

plants. He then went to Messrs. Easton, Anderson and Goolden, for whom he carried out important water-works installations in India. In 1897 he became a resident engineer on the construction of the Davies Street generating station of the Westminster Electric Supply Corporation. On the completion of this work he was for a short time technical manager of La Compagnie Hydro-Électrique Anversoise in Belgium. He then joined the firm of Messrs. Kennedy and Jenkin, consulting engineers, and was associated with the electrification of the London County Council tramways, the Buenos Aires tramways, and the Hammersmith and City Railway. In 1905 he was appointed electrical engineer to the Great Western Railway, a position which he held for 19 years. He was a well-known advocate of the extended use of electric traction on railways and was a member of the Committee appointed by the Minister of Transport in 1921 to report on the electrification of railways. On retiring from the Great Western Railway in 1924, he became a partner in the firm of J. S. and W. E. Highfield, which then took the name of Highfield and Roger Smith.

He rendered an immense amount of service to the engineering profession, on both the educational and the administrative sides. He was elected a Member of The Institution in 1907, served as a Member of Council in 1912-15, as a Vice-President in 1915-18, and as President in 1919. In the present year (1940) he was elected an Honorary Member, an honour of which he was justly proud.

He also served as President of the Institute of Transport and of the British Section of the Société des Ingénieurs Civils de France. This latter was a specially happy position, as he spoke most scholarly French and had received the decoration of the Legion of Honour.

He took an active part in the World Power Conference and in the British Standards Institution. He served on the Senate of the University of London and was a Member of the External Council for some 10 years. His most important work on that Council was in connection with engineering education. As a labour of love he set himself to provide the students with a boat-house, and after several years' hard work his efforts were successful and the university now has a very fine boat-house at Chiswick.

He will be remembered by his many friends as a great gentleman; in his youth he was a most athletic figure, playing lacrosse for England and also first-class cricket, and he was a beautiful skater and dancer. Unfortunately, some 20 or 30 years ago, he was seized with arthritis which rendered him increasingly lame. There are only a few intimate friends who know with what courage he faced this growing difficulty, about which he never complained. The only thing that remained to him of his old activity was his magnificent eyesight; to the last he did not need glasses.

He had well-developed literary ability and a just appreciation of style, which was a great source of pleasure; he was a pleasant speaker and most interesting and amusing in conversation; he had many friends in all classes and possessed the great gift of acting alike to all men.

In 1902 he married Margaret Isabel, daughter of the

late Dr. G. Carey Foster, F.R.S., sometime Principal of University College, London, and a Past-President of The Institution. J. S. H.

SIDNEY SMITH was born in Yorkshire on the 9th May, 1869, and completed his education at the Yorkshire College, Leeds. He joined the South African General Electric Co. in Johannesburg as assistant manager in 1903, and was appointed managing director of the company in 1923. On his retirement he was appointed chairman of the board in 1928. He died in England on the 13th May, 1939. He was very well known in the commercial life of South Africa and will be greatly missed by a large circle of friends. He married Adele Fittig, who, with one daughter, survives him.

He was elected an Associate of The Institution in 1897, an Associate Member in 1899, and a Member in 1902. W. E.-D.

ALBERT LENNOX STANTON, who was born on the 11th October, 1880, and died on the 24th November, 1939, possessed outstanding courage, ability and honesty. The highest ethical standards permeated and governed his every thought, making him both an example and an inspiration to others.

He carried out extensive survey work in the Rocky Mountains, was assistant engineer in the construction department of the New York Central Railroad, was in San Francisco during the 1906 earthquake, and was engaged on the construction of the Panama Canal. He had wide experience in the field of public utilities, embracing British, American, Indian and Colonial practice. In 1920 he joined the Bombay Electric Supply and Tramways Co. Later the Development Directorate of the Government of Bombay requisitioned his services as electrical and mechanical engineer on their Ambarnath Industrial Area Scheme. In 1925 he investigated and reported on British tramway undertakings, and in 1926 he took up consulting work in England, which he continued until his death.

He joined The Institution as a Student in 1904 and was elected an Associate Member in 1906 and a Member in 1925. In the 1931-32 session he served on the Committee of the Hampshire Sub-Centre. He also took an active interest in the proceedings of the Overhead Lines Association and played a prominent part when President in the absorption of its members into The Institution as the nucleus of the I.E.E. Transmission Section. In 1922 he was awarded by The Institution of Engineers (India) their I.E.E. Premium for his paper on "Railway Electrification, with special reference to Indian conditions." T. S.

HENRY STROUD, M.A., D.Sc., Emeritus Professor of Physics in the University of Durham, was born at Bristol on the 7th August, 1861. He was educated at Bristol Grammar School and later at University College, Bristol, when Silvanus Thompson was professor of physics and principal of the college. In 1880 he was awarded the Gilchrist Scholarship at Owens College, Manchester, where for two years he studied under Balfour Stewart and Roscoe. He was a brilliant student, taking all the available scholarships in mathematics and

physics and went with them to St. John's College, Cambridge. In the 1885 Mathematical Tripos he was bracketed eighth Wrangler. With a natural bent for physics he took, in the following year, a first class in Part II of the Natural Sciences Tripos, and in the same year obtained his D.Sc. in the University of London—in those days by examination and a very stiff one. At Cambridge he came under the influence of Lord Rayleigh, and at a time when Prof. William Garnett, a pupil of Maxwell, was principal of the then Durham College of Physical Science (later Armstrong College and now King's College), he was appointed lecturer in physics there, and a year later was elected professor.

The college in those days was the pioneer of higher scientific education in the north-east. Both Garnett and Stroud were great advocates of popular scientific lectures and Stroud threw himself into this work with characteristic energy. His lectures, on the lines made familiar by those at Owens College, were widely welcomed in the towns of the district. When X-rays burst on a wondering world in 1896 Stroud gave a series of experimental lectures, everywhere crowded to the doors, and this was repeated when radium was discovered and again when radio transmission was in its early stages.

Within the University he took an active part in the rapid development of the college. He was a strong committee man, and on the Council and Senate of the University he had much to do with fostering the applications of physics and mathematics to the engineering activities of the Tyne, then advancing by leaps and bounds. At week-ends he found time to collaborate with the late Lord Armstrong at Rothbury in his experimental researches on "Electric Movements in Air and Water," which were published later with remarkable illustrations. It was not, however, in experimental research that he found most scope and he himself published little, though he was always most keenly interested in the results of experimental research and did much to encourage it in his students, endowing college prizes to that end. He was dean of the Faculty of Science from 1919 to 1921 and vice-principal in 1924-26. He took a leading part in the formation of the department of electrical engineering in the college, transferring much valuable apparatus from his own department for this purpose.

During the 40 years of his professorship he saw and welcomed the growing and close connection between physics, mathematics and engineering. He was a Fellow of the Institute of Physics and of the Physical Society. On his retirement in 1926 he was elected Professor Emeritus by the university in appreciation of the valuable work he had done for the college, whose interests he had, to the end, close at heart.

On the formation of the Newcastle Local Section (now North-Eastern Centre) in 1900 at a time when Silvanus Thompson was President, he joined The Institution as a Member and became Chairman of the Local Section in 1909-10. Until his retirement he took a great interest in it, though he was not specially interested in the ramifications of the subject when they became highly technical.

He died at Gerrard's Cross on September 3rd, 1940, and is buried there. W. M. T.

WILLIAM EDWARD SUMPNER, D.Sc., who was born in 1865 and died on the 8th May, 1940, had retired from the principalship of the Central Technical College, Birmingham, in 1930. He was connected from the first with the movement inaugurated by the City and Guilds of London Institute for the advancement of technical education. In 1885 he obtained first-class honours in both mathematics and physics in the final B.Sc. examination of London University, and 4 years later took the degree of D.Sc. From 1888 to 1893 he was lecturer in the City and Guilds Engineering College, South Kensington, and in 1894-95 was head of the electrical engineering department, Battersea Polytechnic. He left this post to take up the principalship of the Birmingham Municipal Technical School (later the Central Technical College). This college had been in existence only 4 years and there were still many people who were dubious of the benefits to be derived from technical education. Dr. Sumpner must be given the credit for the wise guidance of the college through its early stages and its subsequent development. During the 35 years in which it was under his leadership the college made remarkable progress and played an ever more important role in the educational life of the city.

He will be remembered with affection by the generations of students who passed through his hands. Quiet and unassuming, he was a man of delightful personality and human qualities. Students and members of the staff found him always helpful and friendly. When he retired in 1930 one of the methods adopted by his colleagues and former students to perpetuate his name was the foundation of a special Sumpner Prize in Mathematics and Physics. His eminent services to the college were recognized when, in 1936, the honorary associateship of the college was conferred upon him.

Whilst he was a man of unusual distinction in physics and mathematics, he considered himself primarily an electrical engineer. Probably owing to his early association with one of the pioneers of electrical measurement, W. E. Ayrton, Dr. Sumpner's main work lay within this field. At an early stage in his career he was investigating the, at that time, difficult problem of power measurement in a.c. circuits. In 1891, in collaboration with Ayrton, he described in a paper read before the Royal Society the now familiar three-voltmeter method of power measurement. In March, 1891, he pointed out that for every problem involving alternating potential differences in series there was an analogous problem involving alternating currents in parallel, and these ideas were further developed before the Physical Society in June, 1891.

His initial work at Birmingham was on the use of iron in alternating-current instruments. In 1905 he described, in a paper before The Institution, new iron-cored instruments for a.c. measurements, and this was followed by a similar paper in 1907, this time in collaboration with J. W. Record. In 1910, before the Physical Society of London, and in collaboration with W. C. S. Phillips, he described his a.c. galvanometer.

During this period he had interested himself also in the question of phase. In 1904 he described methods of measuring small differences of phase, and in 1905 he

outlined the theory of the then known phase-meters. Both papers were read before the Physical Society. Power work claimed his attention in connection with transformer and motor efficiency measurements, and many members will recollect the standard college Sumpner transformer test.

Throughout his career he was interested in the vector method of attack, both in its restricted sense, as applied to a.c. problems, and in its more generalized forms. In the later part of his career he studied and interpreted Heaviside. He was honoured by The Institution in being chosen to give the 23rd Kelvin Lecture in 1932. He took as his subject the work of Oliver Heaviside. It is obvious that in giving this lecture Dr. Sumpner was performing a task of gratitude. In this and other lectures he showed that he possessed many of the virtues of Heaviside himself particularly those of lucidity and precision, whilst in the Kelvin Lecture there appear at times traces of Heaviside's dry and caustic humour and brilliant turn of phrase.

He was elected an Associate of The Institution in 1887 and a Member in 1898, and served for many years on the Committee of the Birmingham Local Section, being Chairman in 1904-5.

D. S. A.

FRANK TANDY, who died on the 21st April, 1940, at the age of 71, commenced his career in the Post Office Engineering Department in 1891 at the East Dean repeater station. In 1894 he was transferred to the engineer-in-chief's office, where he was engaged on the development of new ideas in electrical communication, particularly the application of the oscillograph to the analysis of telephone speech and the experiments on the first heavy-gauge trunk lines. He also did pioneer work in wireless communication.

During his 12 years at headquarters he was promoted first-class engineer in 1898, and second-class technical officer in 1902. In 1906 he was appointed assistant superintending engineer in the Metropolitan Central District, and in 1911 superintending engineer of the South-Eastern District, a position which he held for 17 years until his retirement in 1928.

The writer's chief association with Mr. Tandy, apart from the most friendly social relations, was in connection with early telephone developments and pioneering work in early radio investigations, in which he took exceptionally keen interest. As a case in point he was one of a small band of young communication engineers who, shortly before the introduction of the vacuum valve, had believed in the possibilities of the cathode stream as a means toward the development of a telephone repeater. Attendance at a series of evening lectures on vacuum tubes, delivered by Dr. R. S. Willows, at the Sir John Cass Technical Institute gave considerable impetus to the idea. At that time the control of the cathode stream by magnetic or electric means had already been demonstrated by Sir William Crookes and others; amounting, in essence, to the provision of a third electrode disposed, in general, outside the valve—a forerunner of the amplifying valve developed later.

It is also perhaps worthy of note that Heaviside's radiational theory of transmission along circuits was

regarded by those young engineers as having exceptional theoretical importance, some of its implications being considered as revolutionizing electrical theory concerning the flow of electricity along conductors. Mr. Tandy was a supporter of this view, though electrical authorities do not yet accept the implications.

He joined The Institution as an Associate in 1891, and was elected an Associate Member in 1903 and a Member in 1922.

J. E. T.

SIR JOSEPH JOHN THOMSON, O.M., F.R.S., Master of Trinity College, Cambridge, died on the 30th August, 1940. His death leaves a much lamented gap in the ranks of the Honorary Members of our Institution. The personal regard in which he was held, the high esteem with which electrical engineers universally revered him, the zeal and enlightenment with which he inspired his audiences when he brought to their notice new phases of his recondite studies, all conduced to appreciation of his qualities. With but slight modification it may be said of him, as it was of another Master of Trinity, that since Bentley there have been none more worthy to preside over the greatest of English colleges. It is well to remind ourselves that it was at that same centre of erudition that Newton began to develop his work on radiation phenomena; for in 1664, as a Scholar of Trinity, he bought his prism. As an indication of the rate of growth of knowledge touching the fundamental conception of radiation processes, from Newton to Joseph Thomson, across the centuries, there remains in the treatise on "Opticks," Newton's unanswered Querie 29: "Are not the Rays of Light very small Bodies emitted from shining substances? For such Bodies will pass through uniform Mediums in right Lines without bending into the shadow, which is the Nature of the Rays of Light." With many other physicists, Faraday, Young, Clerk Maxwell, Hertz, Crookes and Heaviside sought an answer to the riddle, and Joseph Thomson may be said to have made it the basic theme of his investigations. For all his learning, he was neither a pedant nor ponderous. At the thought of cricket, football, or a cross-word puzzle well done, there was sunshine among the shadows. Who that was present can forget the happy mood of his lecture at the Royal Institution on the 18th March, 1910, on the dynamics of a golf ball? To illustrate the path of the ball, a stream of negatively charged particles from a red-hot piece of platinum, with a spot of barium oxide on it, travelled along the vacuum-tube containing the platinum strip, and between two plates at different potentials. A vertical electric field represented gravity, a magnetic field exemplified the force acting on a "properly spinning golf ball"; and here were all the elements for a first-class controversy upon a problem of perpetual elusion.

Although his full name was Joseph John Thomson, there are many who will prefer to think and speak of him with affection as "J.J." This will be in accord with the custom honoured in the previous school of mathematical physicists. Sir William Rowan Hamilton was "H," Sir William Thomson (Lord Kelvin) was "T," Peter Guthrie Tait was "T'," and Clerk Maxwell was " dp/dt ." It had to be explained, however, that $dp/dt = JCM$ were Maxwell's initials, provided that J represents Joule's equivalent, C Carnot's function, and

M the rate at which heat must be supplied per unit increase of volume, the temperature being constant.

In his autobiography, published in 1936, Sir Joseph tells us that he was born in Cheetham, a suburb of Manchester, on the 18th December, 1856, and he explains that his becoming a physicist was "a mere accident." It was intended that he should be an engineer; but the firm of locomotive builders where it had been proposed to apprentice him on leaving a private day-school had too long a waiting-list to give him timely admission. Fortunately, it happened that another Manchester boy, "young John Hopkinson," had just been announced as Senior Wrangler, greatly to the credit of Owens College where he had been trained for Cambridge. It was accordingly decided that Joseph should be given a chance to follow in John's steps, and although he was only 14 years of age the doors of Owens College were opened to him. He has recorded some of his impressions concerning the tuition he there received. The propositions of the First Book of Euclid had to be learnt by heart, there was no algebra but much arithmetic, and he retained the opinion that arithmetic is the best introduction to mathematical ideas. He took the engineering course under Osborne Reynolds. For lecture notes on that subject, however, he trusted mainly to Rankine's text-books. Physics he began under the guidance of Balfour Stewart, chemistry under Roscoe, and he came into touch with Arthur Schuster and Poynting. With such influence, how could a youth of his strength, zeal and intellect fail? His life as an undergraduate was pleasant though uneventful, the kind of existence described for us once for all in an early part of Wordsworth's "Prelude."

He entered into residence at Trinity College, Cambridge, in 1876 and sat for the Mathematical Tripos in January, 1880—an experience arduous, anxious and uncomfortable, for it was "horribly cold," though the ink did not freeze. In the Senate House there were no heating appliances of any kind. Physical subjects had been introduced since 1873 into the Tripos. They included electricity and magnetism, and Clerk Maxwell was one of the examiners "specially qualified to deal with these subjects." In that year, 1880, Larmor appeared as Senior Wrangler, Joseph Thomson as Second Wrangler and Smith's prizeman. Thomson was forthwith elected to a Fellowship at Trinity, and in 1883 he was made lecturer there, in mathematics. In 1884 he succeeded Lord Rayleigh (3rd Baron) as Cavendish Professor of Experimental Physics in Cambridge University, a chair subsequently occupied by Lord Rutherford.

He was knighted in 1908. From 1915 to 1920 he was president of the Royal Society, and it was during this period, in 1918, that he was appointed by the Crown to be Master of Trinity. This obliged him to resign from the Cavendish Professorship and from a professorship at the Royal Institution, where his lectures had been warmly appreciated. He was, in 1906, awarded the Nobel Prize, in 1912 the Order of Merit, and in 1938 the Kelvin Gold Medal.

His achievements are beyond the scope of this brief account to enumerate. They are recorded in innumerable books and journals in our Library, and evidence of them endures and glows in the laboratories of the world at

large. His discoveries take pride of place, but to him the circumstance of equal moment was the extent to which his views stimulated others to devote themselves to research, the vast array of universities and learned societies in which his pupils had professorships, and the number of his Cavendish Students elected as Fellows of the Royal Society. By steadfast devotion, concentrating upon his task his vast powers of penetration, he disintegrated the atom and imparted new life to intra-atomic physics. For a precise account of events leading to these discoveries, and of their relationship to advances made by other investigators, students may find it useful to refer to the treatise by F. Soddy on "Radio-activity," published in 1904, and to "Physical Chemistry" by John Eggert, translated by S. J. Gregg and edited by W. Caspari, which was published in 1932. The Institution elected him an Honorary Member in 1907 and awarded him the Faraday Medal in 1925. The subjects dealt with by him in communications to The Institution include the magnetic and electric effects produced by the motion of electrified bodies, the properties of the electric field, the discharge of electricity through exhausted tubes without electrodes, the velocity of cathode rays, the theory of the electrical conductivity of metals, and the mechanics of the electric field.

He married, in 1890, Rose Elizabeth, daughter of the physician, Sir George Paget. There is a daughter, Joan, and a son, Professor George Paget Thomson, F.R.S. On the 4th September, 1940, the ashes of Sir Joseph Thomson were laid near where Lord Rutherford and Lord Kelvin were buried, in the nave of Westminster Abbey. R. A.

JOHN HENRY TONGE, of Preston, who died on the 17th July, 1940, at Manchester, at the age of 72, joined The Institution in 1887 as a Student, and was elected an Associate in 1890 and a Member in 1897. He received his technical education at Finsbury Technical College, and subsequently was employed by Messrs. Crompton and Co., S. H. Johnson and Co., and L. Clark, Muirhead and Co. After spending 5 years with the last-named firm, holding the position of assistant manager during the latter part of this period, he was appointed engineer and manager of the National Electric Supply Co. at Preston in 1893, and held that post for nearly 30 years. When the company's undertaking was purchased by the Preston Corporation in 1922 he continued to act as engineer and manager to the Corporation Electricity Department, but he resigned 9 months later and set up in practice as a consulting engineer in the town, continuing the practice until the time of his death.

Mr. Tonge was a well-known and respected figure in Preston and took a very active interest in local public affairs. He was elected a member of the Town Council in 1934 and rendered valuable service, particularly in his capacity as Vice-Chairman of the Finance Committee. In addition to his work on the Town Council, he was prominently associated with the Preston Chamber of Commerce and the local Rotary Club, as well as several branches of social service. G. A. R.

BERNARD A. TUBINI, who was born on the 8th February, 1886, was educated at Beaumont College, Windsor, and at the Central Technical College, South

Kensington, where he assisted the late Mr. Duddell in the latter's research work. He then served a 4-years' pupilage with Messrs. Dick, Kerr and Co. (now the English Electric Co.) at Preston. After assisting the late Dr. R. Thury for a few months he was appointed in February, 1911, assistant engineer by the Constantinople Telephone Co. He resigned in August, 1913, and set up as a consulting engineer at Istanbul. In this capacity he prepared plans and specifications for a number of lighting and power plants in Turkey. In addition to his consulting work he served from 1917 up to the time of his death in June, 1940, as professor of electrical engineering in the Robert College Engineering School at Istanbul. In recognition of his services to British interests in Turkey he was elected in 1918 President of the British Chamber of Commerce of Turkey and served in that capacity for the full term of 2 years. He was elected an Associate Member of The Institution in 1912 and a Member in 1937. A. P. M. F.

ARTHUR GARNET TUCKER was born on the 9th February, 1880, and died on the 18th April, 1940. In January, 1913, he was appointed assistant electrical engineer at the Ardeer Factory of Nobel's Explosives Co., superintending the running of the power station and the maintenance of the lighting and power installations. From December, 1913, to April, 1915, he was assistant engineer in the firm of Messrs. Fyfe, Wilson and Co., Glasgow, and was responsible for the design, inspection and testing of electric generating plant and switchgear. He then became senior partner in the firm and occupied that position for a number of years. From November, 1932, until his death he was employed by the Bergius Co., marine oil-engine manufacturers, as their travelling representative. He was also in charge of the firm's stands at the various Exhibitions at which they were represented. He was elected an Associate Member of The Institution in 1913 and a Member in 1920.

PETER WILLIAM WILLANS, M.A., son of the inventor of the central valve engine, was born at Frimley in 1892 and was educated at St. Ronan's, West Worthing, Rugby School and Hertford College, Oxford, where he held a mathematical scholarship and obtained his B.A. and M.A. degrees in 1919 and 1920 respectively. During the Great War he held a commission in the Garrison Artillery and served both at home and in Mesopotamia, and subsequently obtained a Government grant for an improved range finder. In February, 1921, he obtained an appointment as engineer in the service of Marconi's Wireless Telegraph Co. and later became chief of the company's research department. Resigning in 1924, he set up in business on his own account. A few months later he was appointed chief of the research department of the Igranic Co., but in May, 1927, again engaged in various activities on his own account while continuing to act as part-time consulting engineer to the company. From February, 1928, to November, 1931, he was in charge of the research department of the Columbia Graphophone Co. and carried out much work in connection with studio acoustics, the design of recording apparatus, and investigations into supraheterodyne receivers. In November, 1932, he was employed by

Electrical and Musical Industries, Ltd., as a research engineer on the development of television apparatus. Later he set up in practice as a consulting engineer. Shortly after the outbreak of war in September, 1939, he took up an appointment at the Royal Aircraft Establishment, Farnborough, and died on the 28th June, 1940, as the result of an accident.

He joined The Institution as an Associate Member in 1928 and was elected a Member in 1933. He read a paper entitled "Low Frequency Inter-valve Transmitter" before the Wireless Section in 1926 and frequently took part in discussions before that Section.

WILLIAM BRADLEY WOODHOUSE, a Past-President of The Institution, who was born in London on the 3rd April, 1873, and died on the 31st March, 1940, was educated at Finsbury Technical College and University College, London. He served his apprenticeship with the India Rubber and Gutta Percha Co., at Silvertown, and subsequently carried out constructional and other work for various firms, including Messrs. John Davis and Sons, the Cork Electric Tramways Co., and Messrs. Marks and Clerk. In 1896 he became lecturer on mathematics, graphic statics and mechanism, at Finsbury Technical College, where he was assistant to Prof. W. E. Dalby, but he resigned this appointment in 1900 on joining the Newcastle-upon-Tyne Electric Supply Co., with whom he held for a short time the position of resident engineer at the Neptune Bank station.

Three years later he commenced his association, which extended over 36 years, with the Yorkshire Electric Power Co., first as engineer and manager, and from 1936 as managing director. There is hardly a branch of the electric supply industry to which he has not made a notable contribution. In 1905 he introduced the 3-phase 4-wire system of distribution at 400/230 volts, which was later standardized nationally. He was a pioneer in the development of overhead-line transmission and distribution, and his undertaking was the first to adopt a coal clause in supply agreements. During the war of 1914-1918 he acted as assistant to the Coal Controller in Yorkshire, and as Electrical Adviser to the Minister of Munitions in respect of various factories.

He joined The Institution as an Associate Member in 1902 and was elected a Member in 1913. In the same year he was Chairman of the Yorkshire Local Section (now the North Midland Centre). Three years' membership of the Council and three years as Vice-President followed, and he again served as Chairman of the Local Centre before being elected President of The Institution for the 1924-1925 session. His Inaugural Address was marked by the clear insight that it showed into the economic, commercial, political and technical aspects of many subjects which came under review. This breadth of outlook was characteristic of his career.

Among the papers which he read before The Institu-

tion were the following: "Commercial Aspect of Electric Power Supply" (vol. 40), "Overhead Line Construction" (vol. 44), "Distribution of Electricity" (vol. 59), and "Overhead Electric Lines" (vol. 67).

Mr. Woodhouse was the vice-president of and senior British delegate to the Paris H.T. Conference from 1925 to 1933, and was for a time the Government representative on the International Electrotechnical Commission. In 1927 he made a tour of the U.S.A. and Canada, where he visited a number of electrical undertakings.

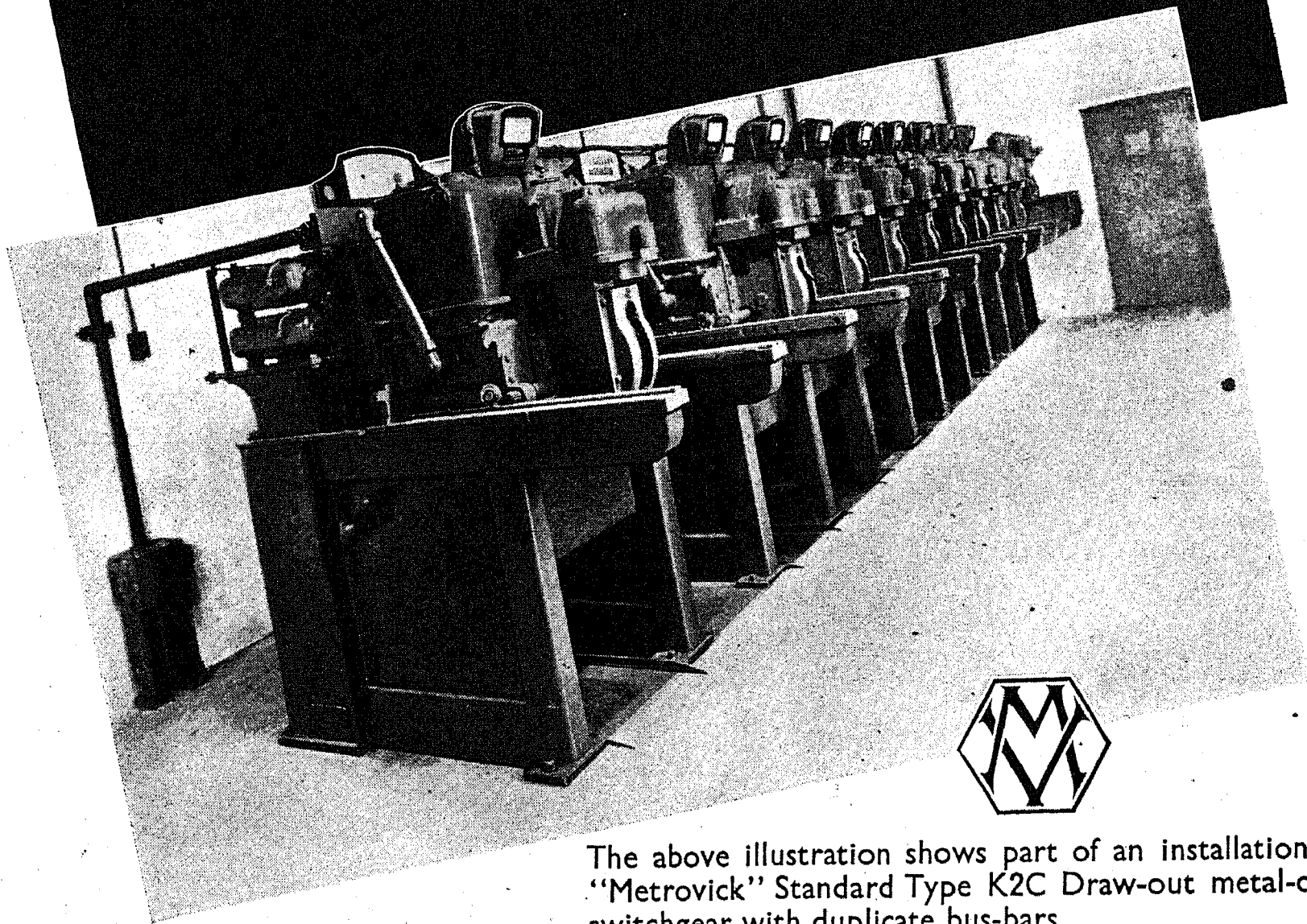
He felt that the electric supply industry was unduly hampered by political and legislative difficulties. On behalf of the power companies he was a forceful advocate of the unification of electricity distribution, with the object of lowering costs and extending the use of electricity, and in this connection he gave evidence before the Williamson Committee, whose Report preceded the 1919 Act, and before the MacGowan Committee, which reported in 1936.

He played a leading part in many organizations connected with the electric supply industry, serving as president of the Electrical Development Association (1923-24), of the Electrical Research Association (1927), and of the Incorporated Association of Electric Power Companies (1930-32), being an active member of the Council of the last-mentioned Association from 1907 until his death. From 1928 to 1940 he was nine times chairman of the Conjoint Conference of Public Utility Associations. From the inception of the Conference he recognized the immense importance of joint consultation and action by the three public utilities—gas, water and electricity. The constitution of the Conference provided that the chairman should be nominated annually by the three groups in rotation. So admirably did he carry out the chairman's functions, however, that on three occasions when those representing the gas interests were called on to make the nomination they waived their right to select a representative of their particular group and unanimously re-elected him.

Among other offices which he filled were those of chairman of the West Gloucestershire Power Co.; member of the Conference called by the Electricity Commissioners in 1933 to advise on national re-organization of electricity distribution; chairman of the Consultative and Technical Committee for the Mid-East England Area of the Central Electricity Board; member of the Midland District Committee of Investigation under the Coal Mines Act, 1930; member of the British Association Committee on Fuel Economy and of the Institute of Mining Engineers Committee on the same subject; member of the Council of the British Standards Institution; and member of the Council of Leeds University and of the Leeds Chamber of Commerce. Among his recreations were shooting, fishing and horticulture. He was an engaging conversationalist, a good raconteur, and a capable and convincing speaker.

H. C. F.

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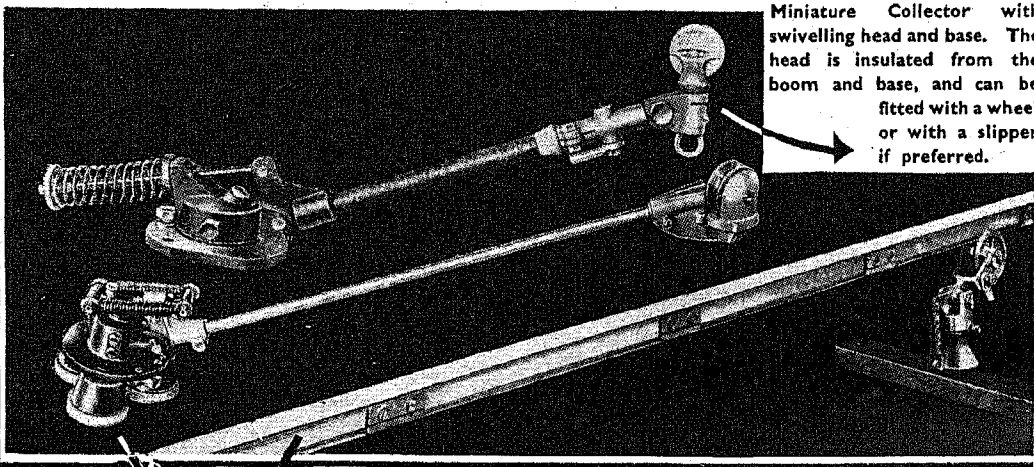
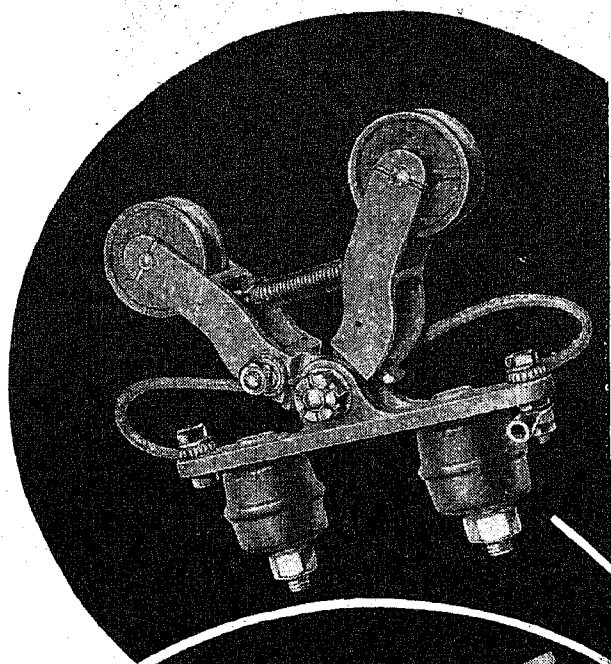
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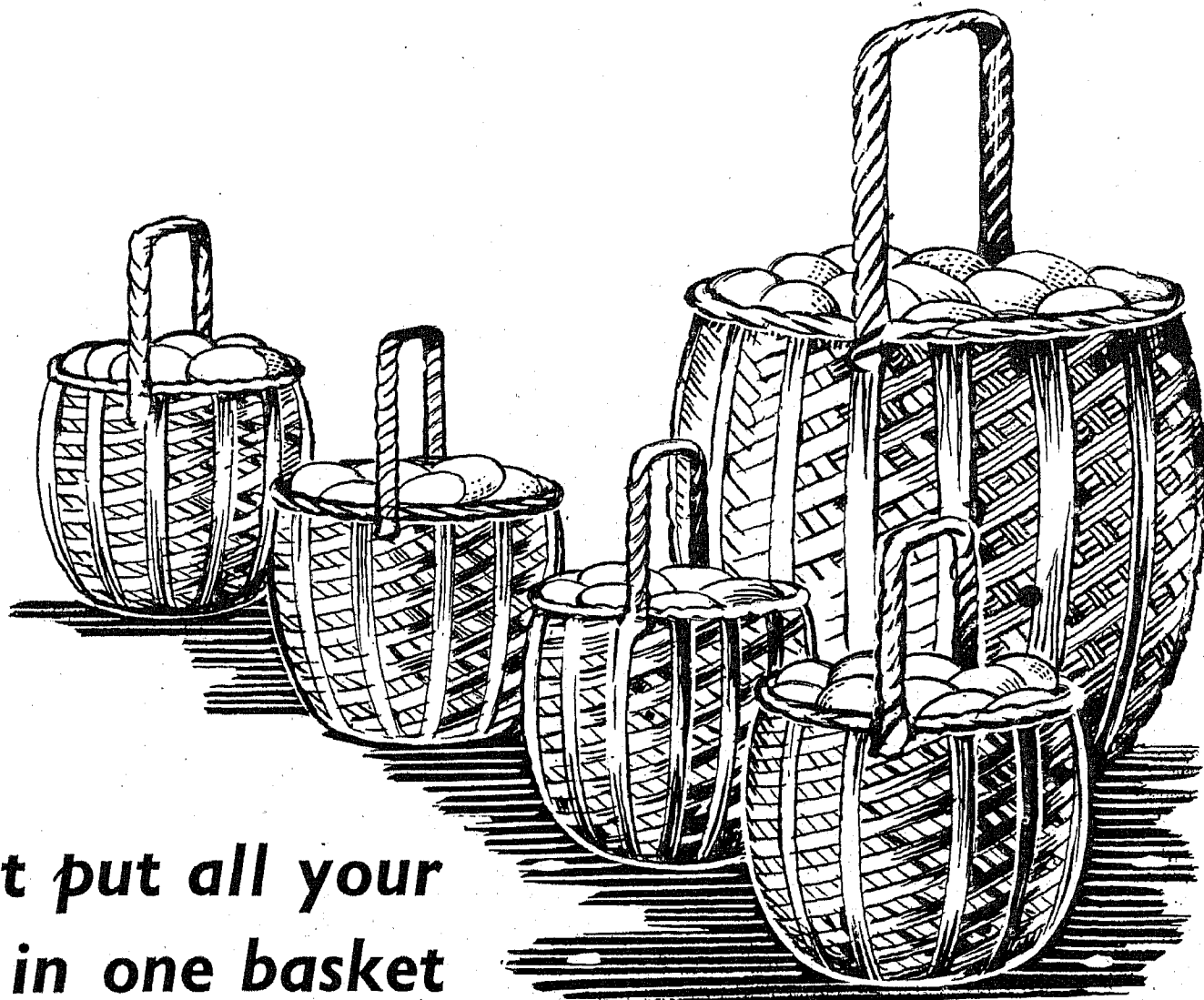
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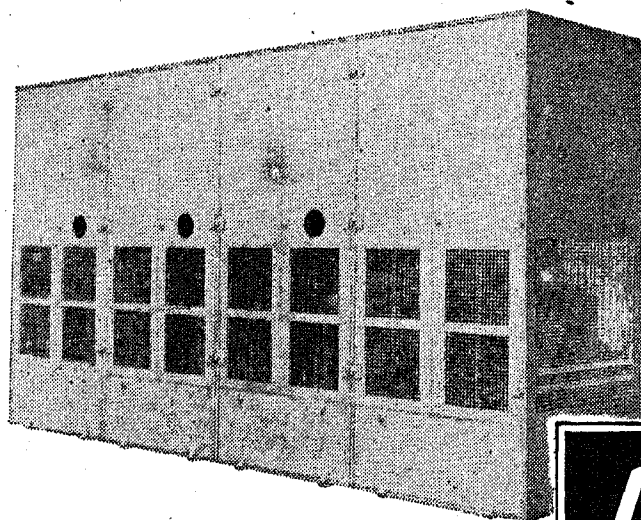


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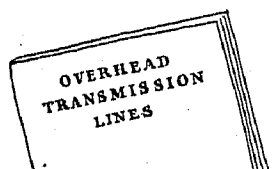
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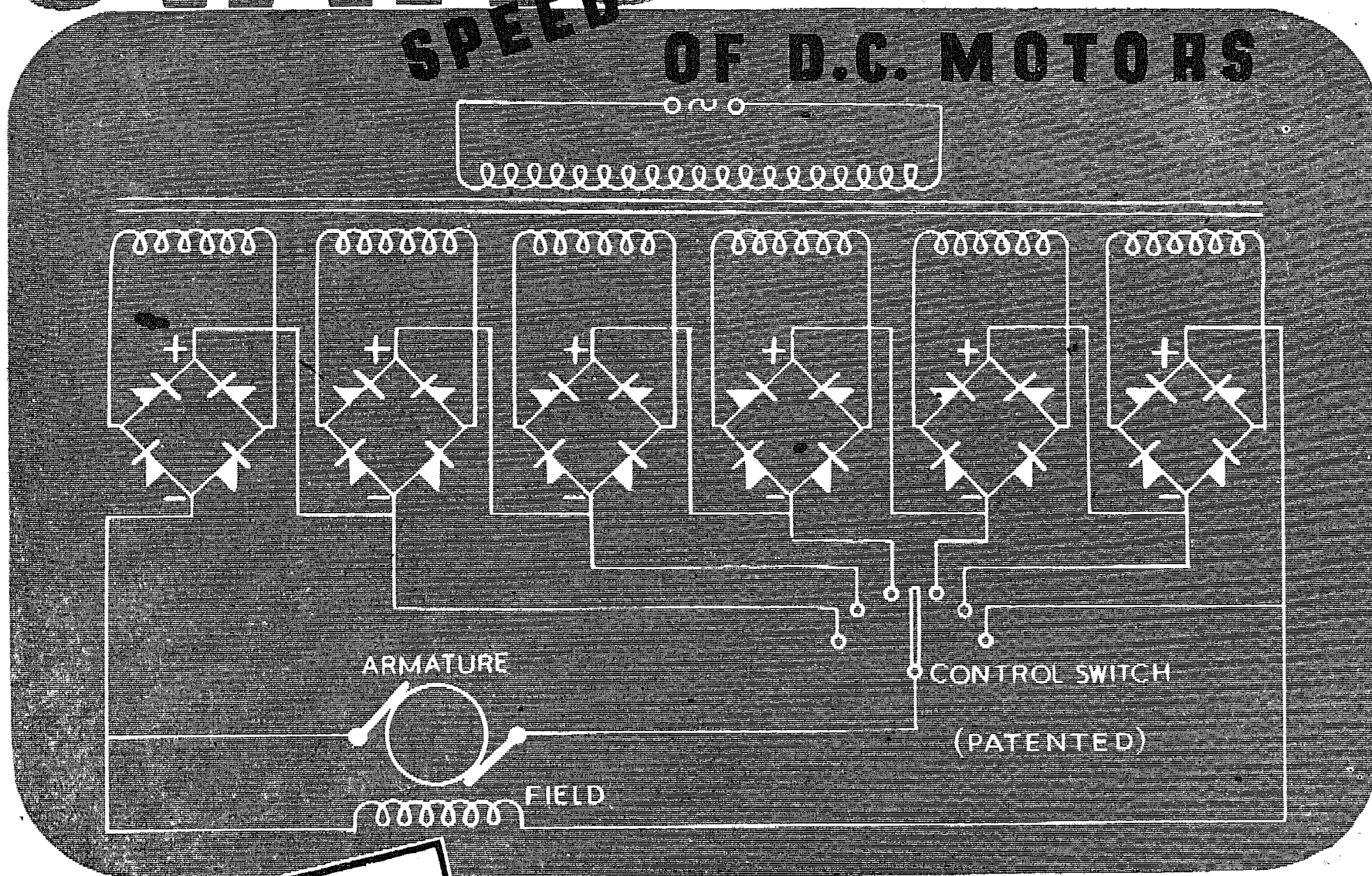
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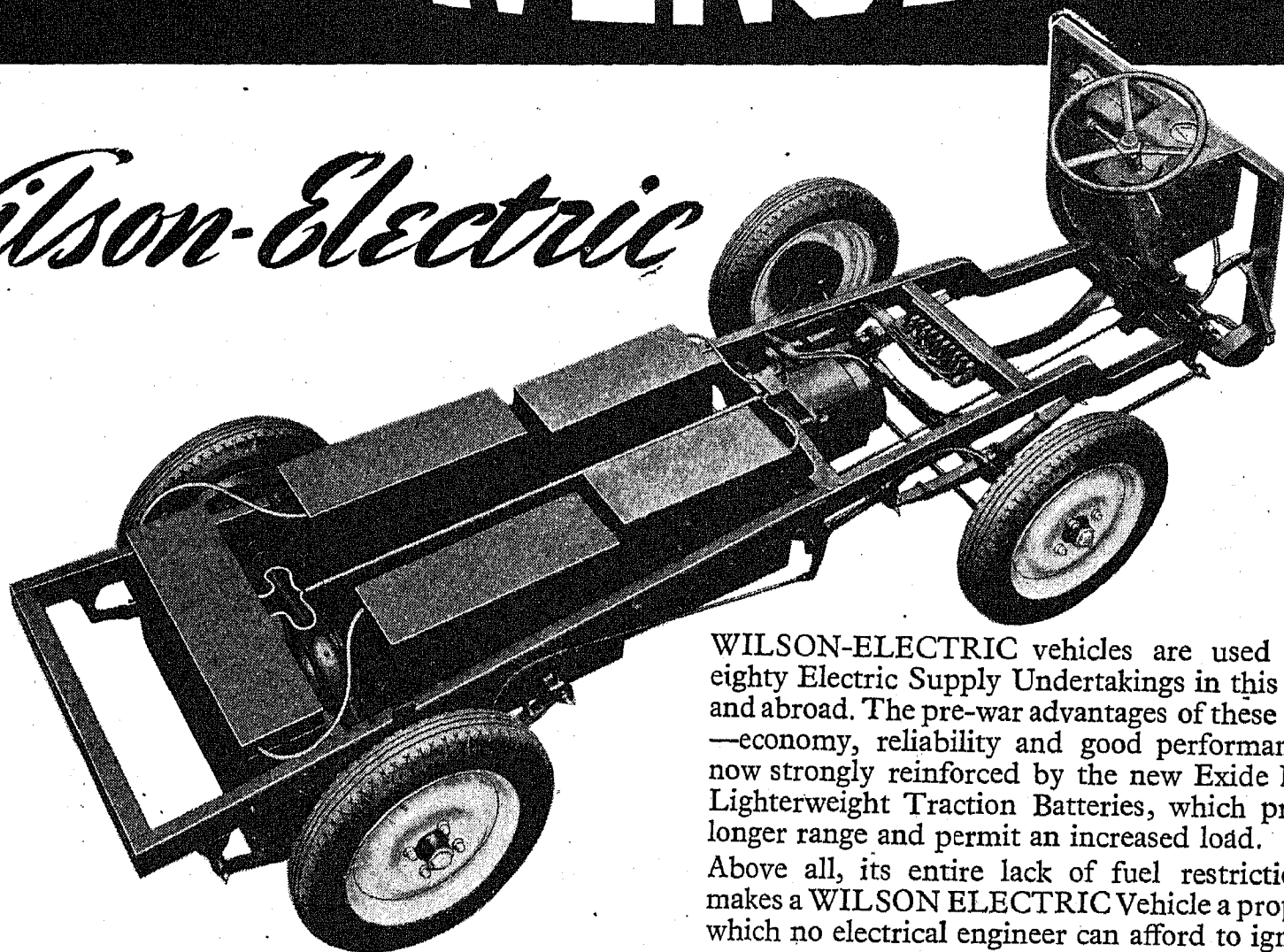
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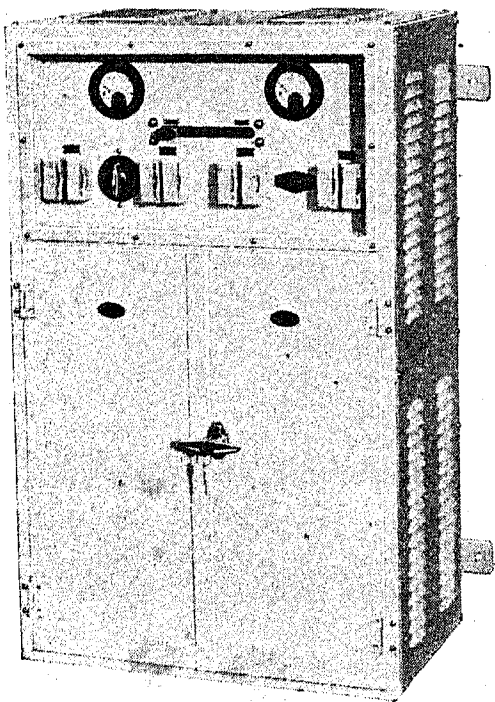
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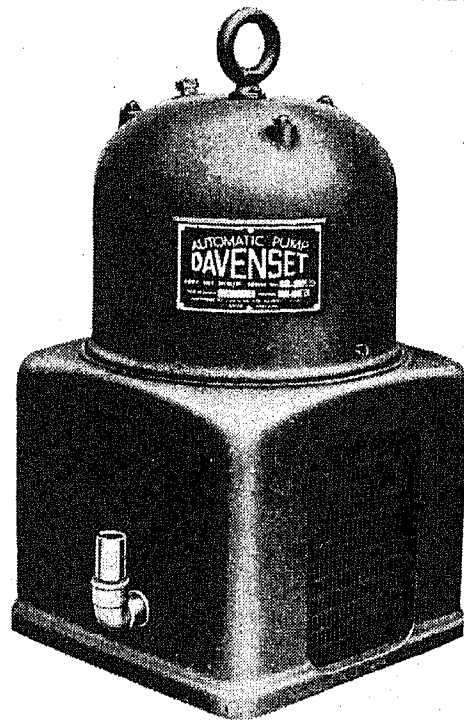
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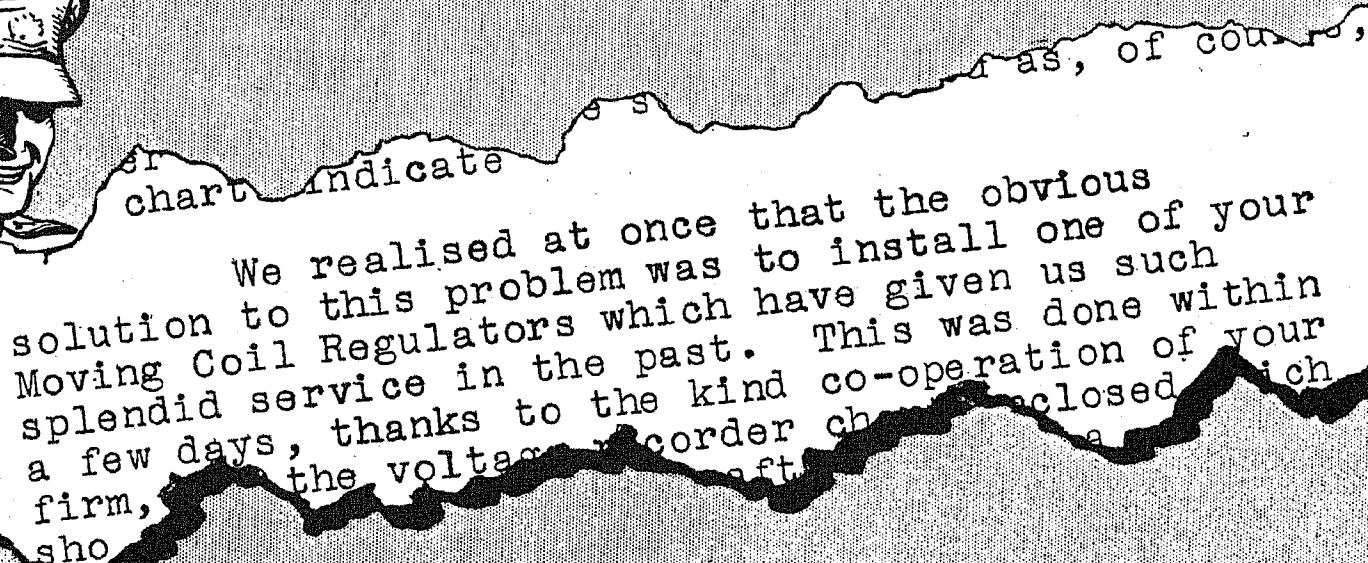
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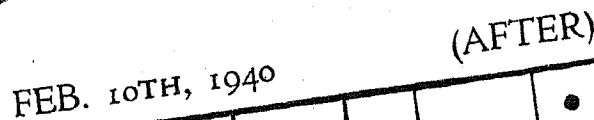
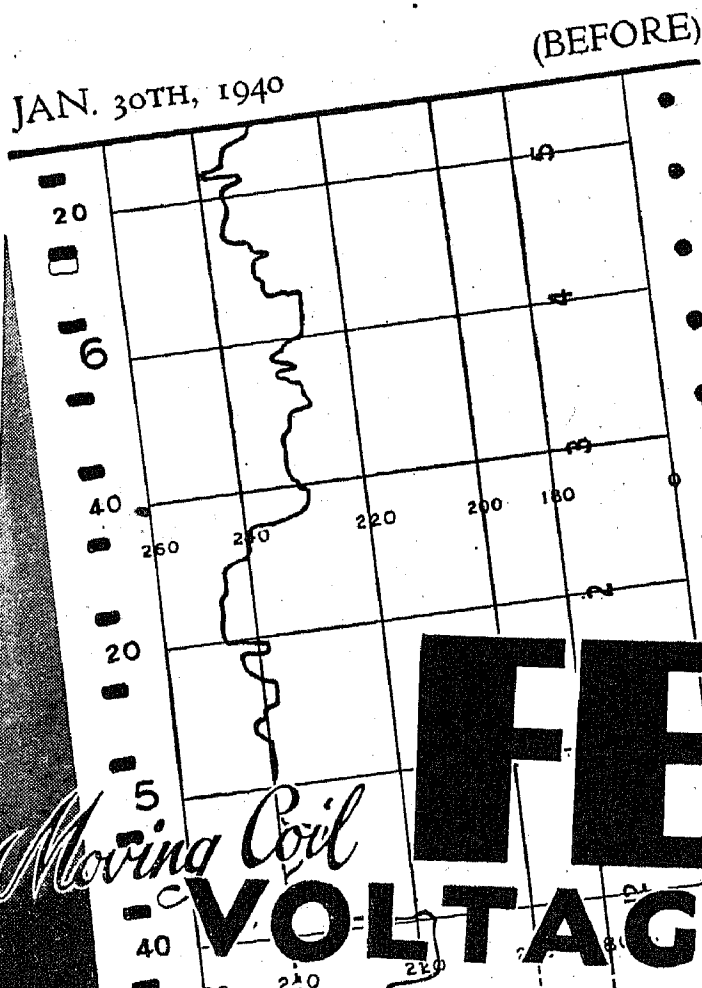
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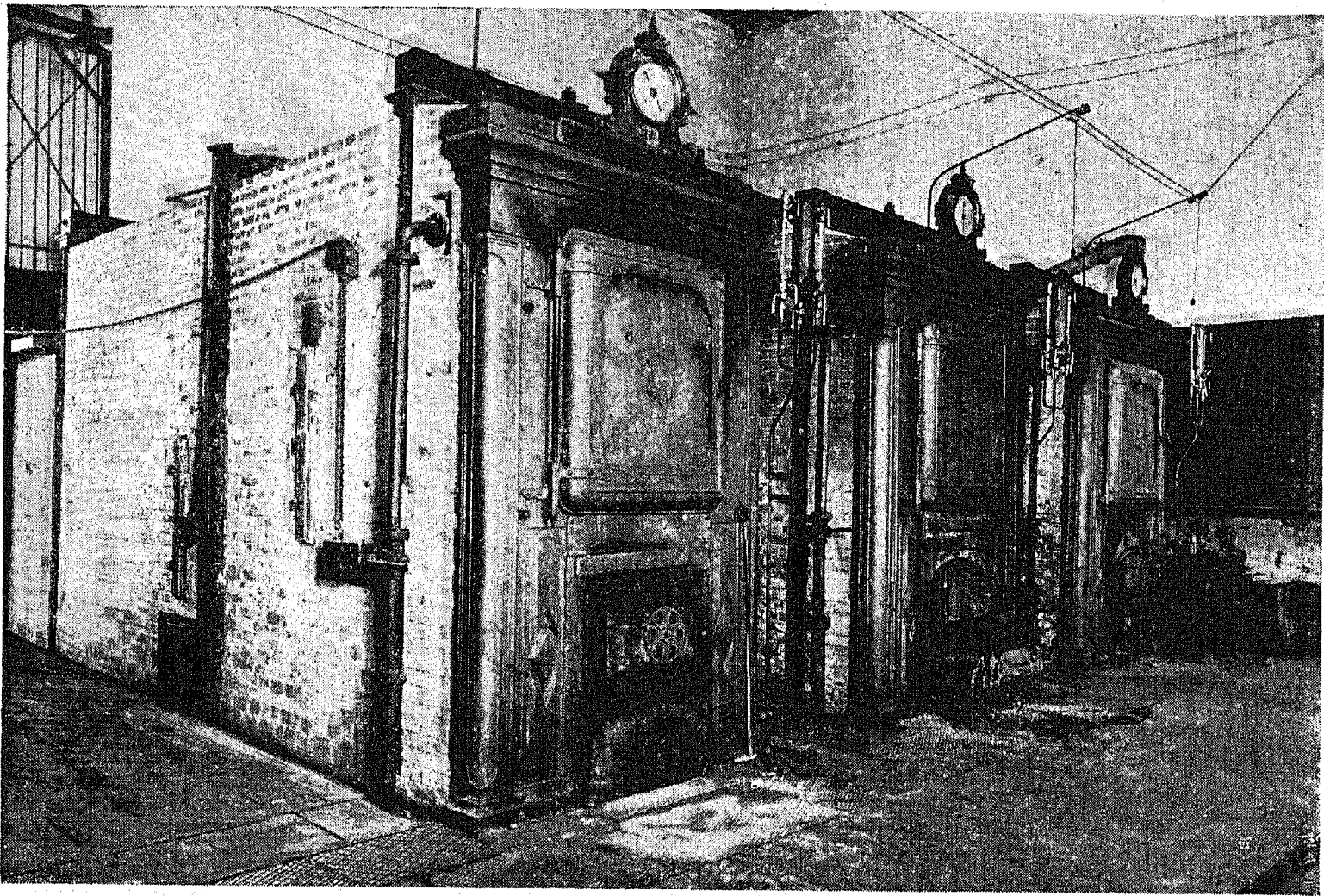
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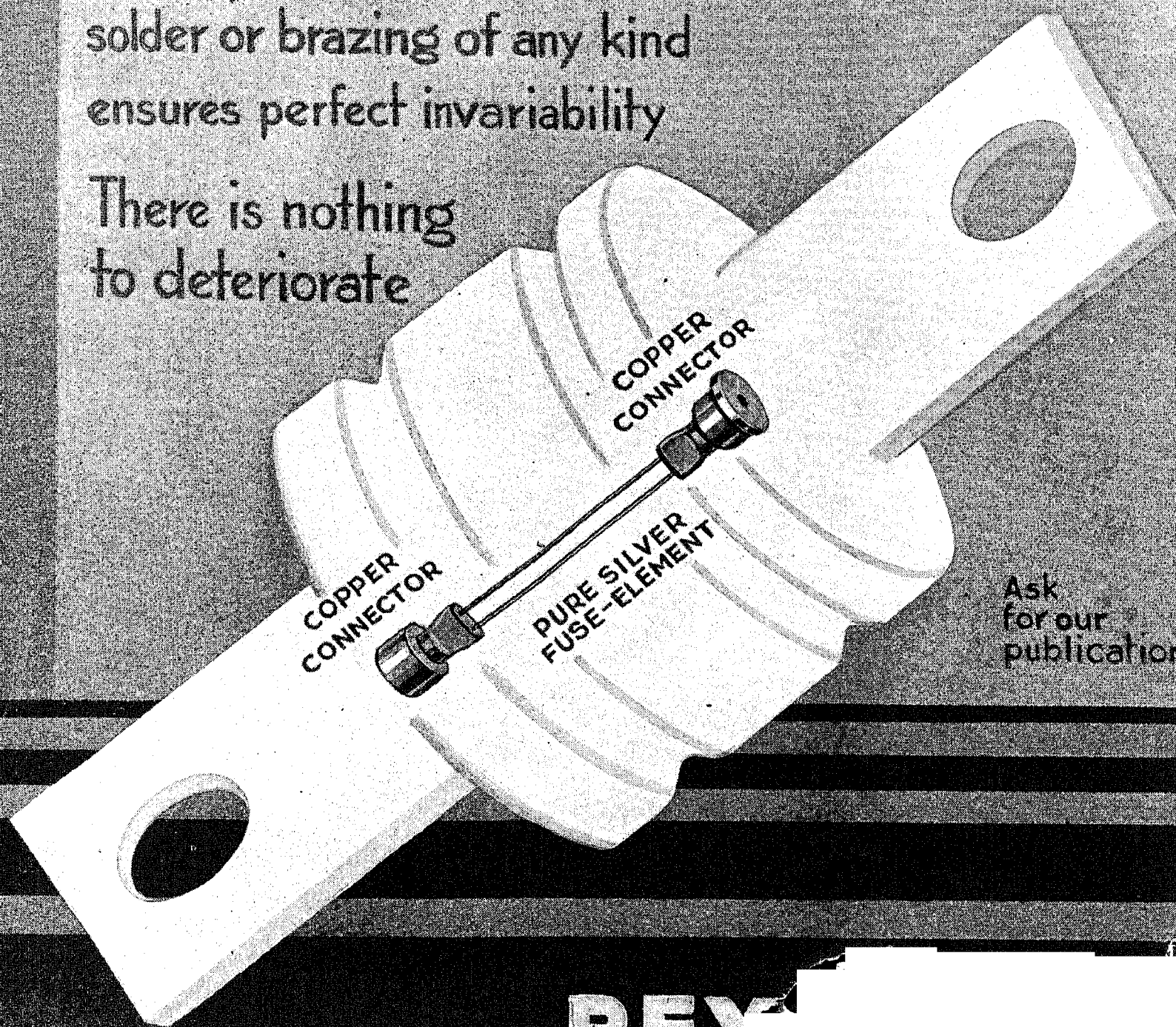
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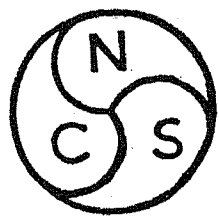
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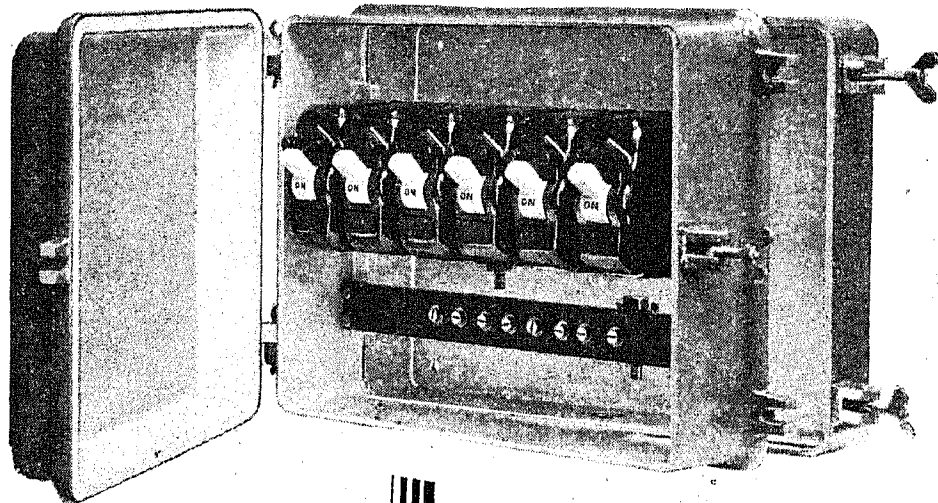
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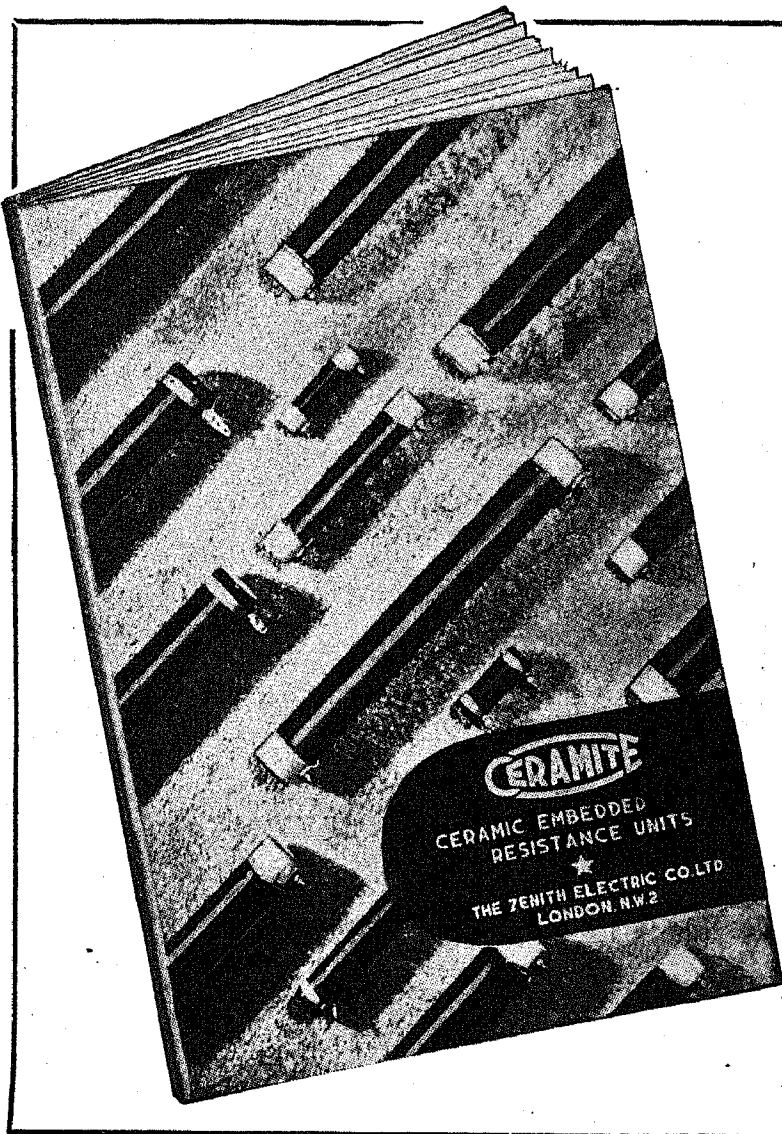
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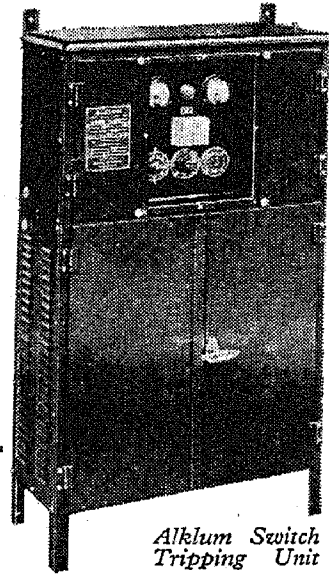
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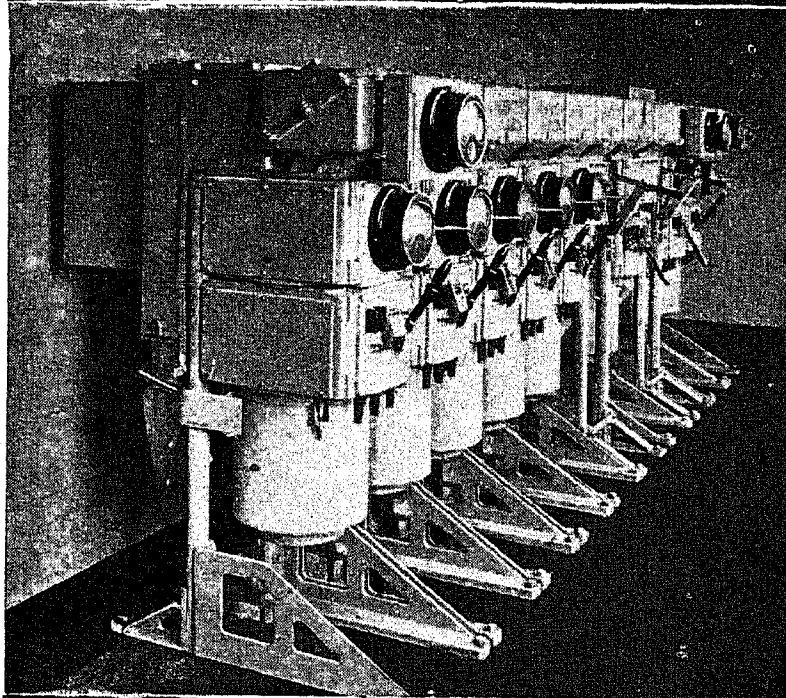
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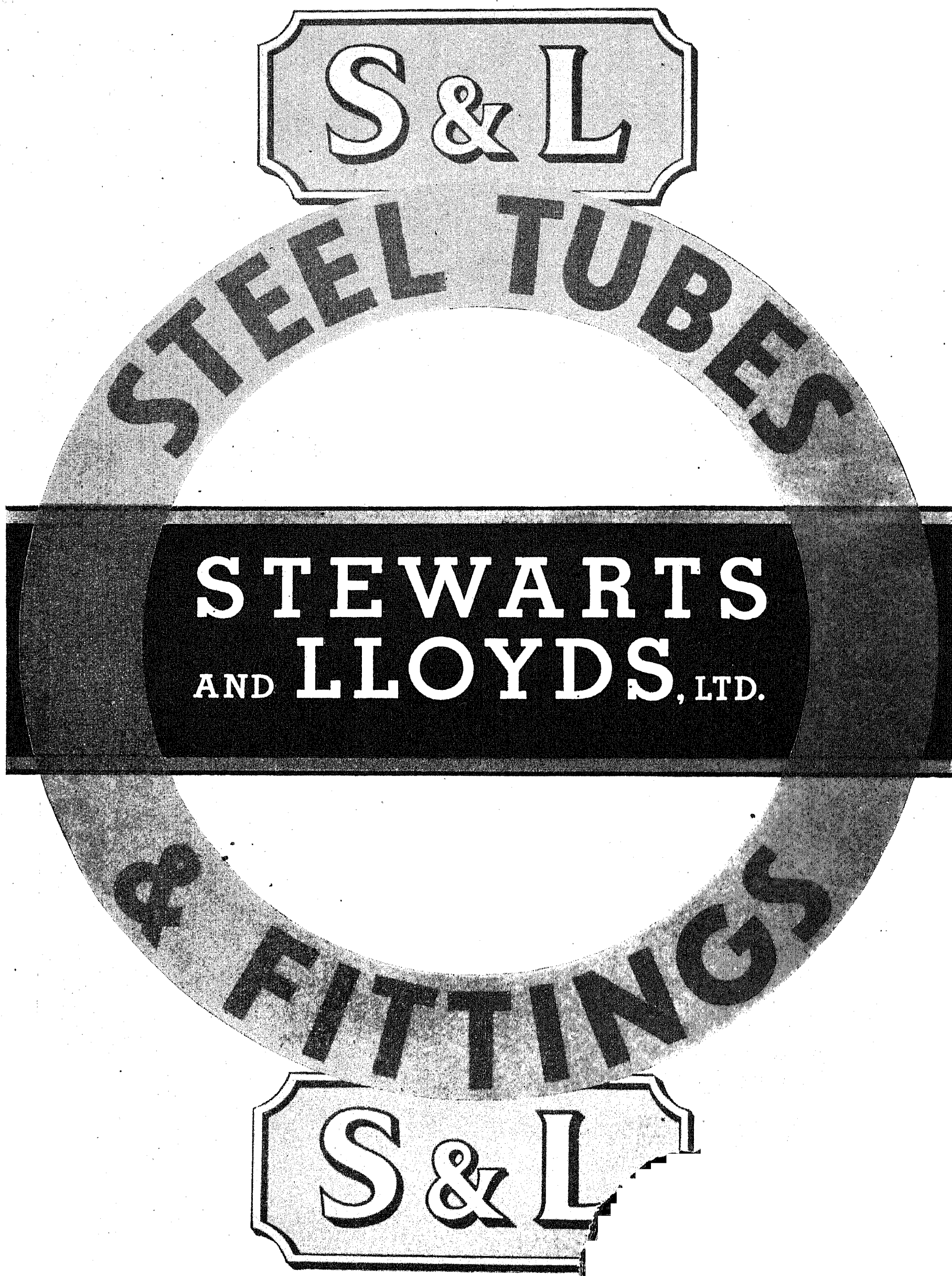
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